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Indirect evaporative cooling: Past, present and future potentials

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ABSTRACT

This paper reported a review based study into the Indirect Evaporative Cooling (IEC) technology, which was undertaken from a variety of aspects including background, history, current status, concept, standardisation, system configuration, operational mode, research and industrialisation, market prospect and barriers, as well as the future focuses on R&D and commercialisation. This review work indicated that the IEC technology has potential to be an alternative to conventional mechanical vapour compression refrigeration systems to take up the air conditioning duty for buildings. Owing to the continuous progress in technology innovation, particularly the M-cycle development and associated heat and mass transfer and material optimisation, the IEC systems have obtained significantly enhanced cooling performance over those the decade ago, with the wet-bulb effectiveness of greater than 90% and energy efficiency ratio (EER) up to 80. Structure of the IEC heat and mass exchanger varied from flat-plate-stack, tube, heat pipe and potentially wave-form. Materials used for making the exchanger elements (plate/tube) included fibre sheet with the single side water proofing, aluminium plate/tube with single side wicked setting (grooved, meshed, toughed etc), and ceramic plate/tube with single side water proofing. Counter-current water flow relevant to the primary air is considered the favourite choice; good distribution of the water stream across the wet surface of the exchanger plate (tube) and adequate (matching up the evaporation) control of the water flow rate are critical to achieving the expected system performance. It was noticed that the IEC devices were always in combined operation with other cooling measures and the commonly available IEC related operational modes are (1) IEC/DEC system; (2) IEC/DEC/mechanical vapour compression system; (3) IEC/desiccant system; (4) IEC/chilled water system; and (5) IEC/heat pipe system. The future potential operational modes may also cover the IEC-inclusive fan coil units, air handle units, cooling towers, solar driven desiccant cycle, and Rankine cycle based power generation system etc. Future works on the IEC technology may focus on (1) heat exchanger structure and material; (2) water flowing, distribution and treatment; (3) incorporation of the IEC components into conventional air conditioning products to enable combined operation between the IEC and other cooling devices; (4) economic, environment and social impacts; (5) standardisation and legislation; (6) public awareness and other dissemination measures; and (7) manufacturing and commercialisation. All above addressed efforts may help increase the market ratio of the IEC to around 20% in the next 20 years, which will lead to significant saving of fossil fuel consumption and cut of carbon emission related to buildings.

Contents

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1. Introduction

The building sector is responsible for around 30–40% of world total energy consumption and similar proportion of global carbon emission [1]. Heating, Ventilation and Air Conditioning (HVAC) is the major energy user in a building and consumes around 50% of the total supplied energy [1]. Air-conditioning, representing an important function of the HVAC system, is becoming increasingly crucial for many buildings, particularly those public types e.g., office blocks, supermarkets, sport centers, airports, factories etc, owing to recent frequent warm spells, improved building insulation and growth of in-house heat generating appliances. In hot and/or arid regions e.g., Middle East, Far East and North American, air conditioning has become part of the people's life need; whilst its use in mild climatic regions such as UK, Denmark and other European regions is also rapidly growing [2]. During the hottest summer period when air conditioning is in full operation, many cities in China, Kuwait etc. [3], experienced difficult power-overloads that often led to unwanted grid 'cut-off'. Concerning with the extensive need for air conditioning and growing pressure on energy saving and carbon emission in building sector [4], seeking for routes to reduce fossil fuel consumption and increase utilization of natural or renewable energy during air conditioning process is of particular importance.

Air conditioning market is currently dominated by the mechanical vapour compression refrigeration system which, formed as a loop (Fig. 1) comprising an evaporator, a condenser, a compressor and an expansion valve, allows a refrigerant (e.g., R-22, R-134a, R410A) to circulate around. Within the evaporator, the refrigerant absorbs heat from the surrounding causing change of its phase from liquid to vapour and subsequently the cooling of the surrounding medium (e.g., water, air). Afterwards, the refrigerant is fed into the compressor which, through delivering a significant electrical power, enables generation of a high pressure, super-saturated refrigerant vapour. This form of vapour then enters into the condenser; whereas it loses heat to surrounding medium, leading to condensation of the high pressure refrigerant vapour. Leaving off the condenser, the refrigerant comes across an expansion valve which, through the throttle effect, causes reduction of the refrigerant's pressure. This low pressure refrigerant is then back to the evaporator to recollect the heat. This kind of cycle was fully established and has been in practical use for over 100 years. Owing to its relatively long history and massive scale production, the technology presents many advantages e.g., good stability in performance, low cost, long life cycle time and reasonable good energy performance (COP in the range of 2–4). However, this type of system has a major disadvantage that lies in high demand to electricity for operation of the compressor. Owing to the high dependency of fossil fuel burning in current electrical industry, this technology is regarded as neither sustainable nor environmentally friendly [5].

Absorption and adsorption cooling, as a potential alternative to conventional mechanical vapour compression systems, remove need for the power-intensive compressor but add up requirement for high temperature vapour or water. The absorbent system is a liquid desiccant cycle comprising a desiccant absorber, regenerator, condenser, evaporator, expansion vale and piping connections, as shown schematically in Fig. 2. This system would absorb heat on one side (evaporator) to enable cooling of a medium (e.g.,

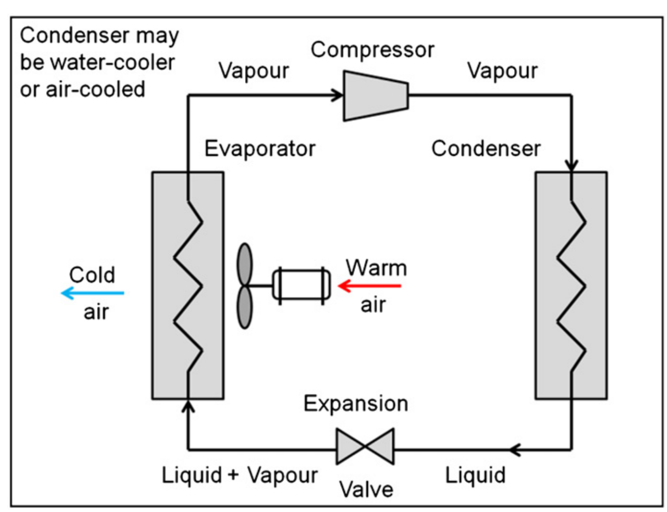


Fig. 1. Conventional vapour compression refrigeration cycle.

Nomenclatures

c	specific heat at constant pressure, kJ/ (kg k)
V	volumetric flow rate, m^3/s
m	mass flow rate, kg/s
Q	cooling capacity of evaporative cooler, kW
t	air flow temperature, °C
w	moisture content, kg/kg (dry air)
i	enthalpy, kJ/kg
u	air velocity, m/s
W	measured total power consumption, kW
ECER	evaporative cooler efficiency ratio, measured at $t_{p,db,in}=32.8$ °C, $t_{p,wb,in}=20.6$ °C, $t_{room}=26.7$ °C
COP	coefficient of performance
EER	energy efficiency ratio, which is the COP multiplied by 3.413.

Greek symbols

ρ	density, kg/m^3
ε	saturation effectiveness

Subscripts

f	air
w	water
p	primary channel
s	secondary channel
db	dry bulb
wb	wet bulb
dp	dew point
in	inlet
out	outlet

air or water) and reject the absorbed heat on the other side (condenser) simultaneously; whilst the absorber and generator in combination act as the thermal compressor of the system. Owing to the need of an expensive and metal-corrosive chemical solution, e.g., LiCl, LiBr, CaCl2 or KCOOH, the system configuration appears to be complex and its cost is therefore high [6]. The adsorbent system has a similar system construction to the absorbent system but uses the desiccant wheel or beds as the replacement of the absorber and regenerator, which accommodate a solid desiccant such as Silica gel, Zeolites, Molecule sieves or Polymer. Both absorption and adsorption systems need heat as a driving force and therefore are only suitable for occasions where heat source is available. These systems have a relatively lower thermal COP in the range 0.4–1.2, which lead to intensive use of heat energy. Further, relatively complex system configuration containing pressurised and de-pressurised components in the absorption and adsorption systems reduces their attraction to users [6].

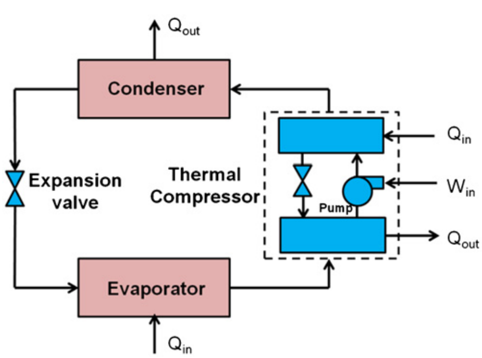


Fig. 2. Absorption cooling cycle.

Over the past decades, evaporative cooling, utilizing the principle of water evaporation for heat absorbing, has gained growing popularity for use in air conditioning [7–9], owing to its simplicity in structure and good use of natural energy (i.e., latent heat of water) existing in ambient. This led to enhanced system COP in the range 15–20, which is significantly higher than that for conventional vapour compression and adsorption/absorption air conditioning systems. Direct Evaporative Cooling (DEC) keeps the primary (product) air in direct contact with water, causing evaporation of the water and reduction of temperature of the air simultaneously. As a result, the vaporised water, in form of vapour, is added into the air, which often creates wetter air condition and causes discomfort to the residents. To overcome this difficulty, Indirect Evaporative Cooling (IEC) was brought into consideration. In an IEC, water is separated from the primary (product) air using the heat exchanging plate [10,11]. During operation, evaporation of the water occurs in one side of the plate where the secondary (working) air moves along; while the primary (product) air flows across the other side. Evaporation of the water causes reduction of the temperature of the plate, resulting in heat transfer between the primary air and the plate. Meanwhile, the vaporised water is taken away by the secondary (working) air across the wet-side of plate. By doing so, the primary air is cooled but no moisture is added into it, which is ideal for purpose of building air conditioning. Owing to this advantage, Indirect Evaporative Cooling (IEC) has potential to become a feasible alternative to conventional mechanical vapour compression systems, which would lead to realisation of low (zero) carbon air conditioning served for buildings.

Biggest problem facing the Indirect Evaporative Cooling (IEC) technology lies in its high level of dependency to ambient air condition. The driving force of either direct or indirect evaporative cooling is the temperature difference between the dry-bulb

Table 1
A general comparison between the currently available air conditioning systems.

System type	Mechanical vapour compression	Absorption/adsorption	Evaporative cooling
Features	Dominate the air conditioning market Mature technology with stable performance and low cost Driven by electricity with COP of 2 to 3 Energy intensive	Driven by heat (waste, renewable or gas) with limited application Complex system configuration and operational status Low COP: 0.4–1.2 Energy intensive	Using water as the cooling medium Simple system configuration and operational status High dependency to the ambient condition High COP: 15 to 20 Energy economic

and wet-bulb (or dew point) of the process air, which, in humid or mild climate regions, is very small and thus leads to very limited system cooling capacity. Further, instability of the ambient air condition (temperature/humidity) also causes unsteady operation of the Indirect Evaporative Cooling (IEC) system [12]. A general comparison among the above mentioned air conditioning systems is indicated in Table 1.

To understand the performance, current status, advantages and disadvantages of the Indirect Evaporative Cooling (IEC), identify difficulties and barriers remaining in the application of this type of system, find out routes toward the enhanced system performance, and study the system's operational modes, a comprehensive review and subsequent analysis into the Indirect Evaporative Cooling (IEC) technology is critically needed and therefore conducted hereby as the major work of the paper. Further, future research focuses on this topic and market potential of the IEC products were also studied.

2. History and current status of the indirect evaporative cooling (IEC) technology

Appearance of evaporative cooling occurred at around 2500 B.C., during which the ancient Egyptians made use of water-containing porous clay jars for purpose of air cooling. This mechanism was also applied into ancient Egypt buildings and further spread across the Middle East regions where the climates are always at hot and arid state. Numerous similar built-ups such as porous water pots, water ponds, pools, and thin water chutes appeared in that time being and many of those were combined into the building constructions in order to create the buildings' cooling effects [13].

The modern evaporative cooling devices were originated from USA. In early 1900s, air washers were invented at New England and Southern Coastline and used for cleaning and cooling air in textile mills and factories. During that period, several air cooling devices including the direct and indirect coolers were also found in Southwest (Arizona and California) region [13]. In late 1930s, many houses and business spaces at Southwest were equipped with individually made water dripping air coolers which, when entering into early 1950s, were developed into the massively producing products and obtained wide range of market places including USA, Canada, and Australia.

Owing to the distinguished advantage of the Indirect Evaporative Cooling over the direct one, i.e., no moisture added into the air thus enabling hygiene air quality, this type of air treatment has gained growing attention and fast development over the past few decades. Research, production and practical application related to the IEC were all rapidly flourishing. From research point of view, focuses were given to (1) computer model set-up of the heat and mass exchanger and accuracy verification and modification using the test results [14–20], optimisation of the geometrical configuration and operational condition related to the exchanger [21], analyses of the system performance in terms of cooling effectiveness, COP, moisture entrains dissipation and thermal resistance [7,8], lab and onsite testing of the exchanger and whole IEC system [22–26], study of the method enabling effective air conditioning for buildings by using the indirect evaporative cooling system and other associated cooling measures, as well as economic and environmental analyses [10,25,27]. In recent years, a new type of indirect evaporative cooling system, known as 'dew point cooling', was developed enabling the outlet air to be cooled to the degree below the wet-bulb of the inlet air and approach its relevant dew point, which was viewed as a breakthrough against traditional direct/indirect evaporative cooling. Researches

Table 2
Selected evaporative cooling manufacturers and their product specifications.

No	Manufacturer	Product model	Technical specifications
1	Munters group [http://www.munters.us/en/us/Products–Services]	Oasis EPX	Hybrid IEC/DX system 5,000 to 15,000 cfm 41 to 112 Cooling Tonnage Based condition: 110F° DB and 75F° WB Maximum EER over 100 Recover 50% of the heat exhausted from the space in winter
		Oasis PFC	Reject up to 2.7 million BTUs of heat at design conditions 62 to 247 GPM Wet/307–1228 MBH Heat Rejection—Wet Operation: 95°F DB, 78°F WB; EWT 95°F, LWT 85°F 72 to 288 GPM Wet/359 to 1436 MBH Heat Rejection—Dry Operation, 50°F DB, 45°F WB; EWT 95°F, LWT 85°F
2	Coolerado Corporation [http://www.coolerado.com/products/]	M30/M50/C60, Stand Alone	Indirect Evaporative Cooling 450/710/710 W or less power consumption Conditioned air flow: 1,530/2,460/2,700 m3/h EER 40+(Energy Efficiency Ratio)
		H 80, Hybrid	Hybrid IEC/and two stage compressor system. EER 21+; an EER of 21.7 at 105°F and an EER of 51.8 at 90°F annual test conditions Conditioned air flow at 2.700 m^3/h with 174.02 Pa external ducting losses
		RF100, Pre-cooling	Indirect Evaporative Cooling Significant energy savings—up to 90% in arid climates High-efficiency hybrid Coolerado cooling with cooling capacity up to 25 t. Combined EER of 20+
3	Speakman CRS [www.speakmancompany.com/files]	OASYS	Indirect/direct (Two stage) evaporative cooling 110% of evaporative effectiveness, 80% of energy savings potential 2.8 gal/ton-hr of water use

Table 2 (*continued*)

No	Manufacturer	Product model	Technical specifications
4	AIR GROUP AUSTRALIA [http://www.coolbreeze.com.au/coolbreeze-model-range.html]	CoolBreeze, Cascade Model Series (C125 to C240)/(D095 to D255)	Direct Evaporative Cooling Energy input: 600–1,000 W Cooling power: 9–16.5 kW/7–17 kW Supply flow rate: 10,000–18,500/7,500–19,500 m^3/h
5	CARRIER [http://www.brivis.com.au]	Brivis Contour Series (L24 to L64)/(P24 to P64)/(F24D to F54D)	Direct Evaporative Cooling Cooling capacity: 8.9–16.7 kW/8.6-16 kW/8.6–15.4 kW (on basis of AS2913-2000)
6	CLIMATE TECHNOLOGY [http://www.climatetechnologies.com.au] [www.waterrating.gov.au/…/evaporative-air-conditioners.pdf]	Celair Profile Series (PS 500 to 850)	Direct Evaporative Cooling Air output flow rate: 9,326–15,986 (m3/h) Energy input: 600–750 W
		Bonaire Integra Series (VSS50 – VSL75)/(SBS50 – SBL 75)	Direct Evaporative Cooling Residential ducted Supply flow rate: 9,085–17,766 (m3/h) Energy input: 970–1,540 W
		Bonaire B&C Series (B18 – B36 and 700C – 1500C)	Direct Evaporative Cooling Commercial ducted Supply flow rate: 9,360–57,060 (m3/h) Energy input: 750–10,000 W
		Bonaire Seasonmaker DF	Direct Evaporative Cooling Commercial, window-mounted Supply flow rate: 13,300 (m3/h) Energy input: 425 W
7	SEELEY INTERNATIONAL [http://www.seeley.com.au] [www.waterrating.gov.au/…/evaporative-air-conditioners.pdf]	Coolair Series (CPL450–CPL1100)/ Braemar Series (LCB250–LCB550)/ Breezair Series (EXH130–EZH215)/	Direct Evaporative Cooling 85% of Evaporation efficiency Energy input: 335–750 W/360–930 W/500–1,500 W/500–1500 W/ Cooling power: 7.3–14.1 kW/8–14.7 kw/8.4–15.4 kw/ Supply flow rate: 2,340 to 10,080 m^3/h
		Braemar Commercial EA series (EA90–EA150)	Direct Evaporative Cooling 85% of Evaporation efficiency Energy input: 550–1,500 W Supply flow rate: 6,840–11,340 m^3/h
		Braemar Commercial RPA series (RPA400–RPA900)	Direct Evaporative Cooling 85% of Evaporation efficiency Energy input: 1,100–4,500 W Supply flow rate: 14,760–31,716 m^3/h
		Braemar Commercial RPB series (RPB600–RPB1800)	Direct Evaporative Cooling 85% of Evaporation efficiency Energy input: 2,000–15,000 W Supply flow rate: 22,032–63,684 m^3/h
		Braemar Commercial RPC series (RPC250–RPC450)	Direct Evaporative Cooling 85% of Evaporation efficiency Energy input: 560–1,500 W Supply flow rate: 6,840–12,240 m^3/h
8	AMAX [http://www.amax.us.com/index.html]	AMAX series (AMAX 055 – AMAX 200)	Indirect/Direct 5,500 to 20,000 cfm Adiabatic effectiveness 115–140% EER 40+ Water Evaporation: 77–280 LPH
9	United Metal Products [http://www.unitedmetal.com]	IDU Series (End discharge, Down discharge and Up discharge)	Indirect-only or Indirect-Direct cooling 4,000 cfm to over 58,500 cfm as standard 78 cataloged sizes and Custom sizes availalbe ETL labeling available
10	WESTAIRE ENGINEERING INC [http://www.westaireengineering.com/index.htm]	Two Stage Indirect/Direct Evaporative Cooler	Comply with UL 1995/CSA C22.2 No. 236 s edition and bear ETL labels Meet the requirements of the United States Government Military MIL-OC-22949C Capacity for standard units 3,000 cfm to 25,000 cfm
		Cel-pack Evaporative Cooler	Comply with (UL 1995/CSA C22.2 No. 236 s edition) and bear ETL labels Self-contained unit incorporating Cel-dek media Cross-fluted self-cleaning design of pads Standard capacities range from 4,000 cfm to 42,000 cfm and special units are built up to 130,000 cfm
		Rotary-Type Evaporative Cooler	Comply with the United States Military Specifications (MIL-OC-22948C) Evaporative efficiency is minimum 85% at 20F wet bulb depression Capacity for standard units 2,000 cfm to 30,000 cfm

Table 2 (*continued*)

No	Manufacturer	Product model	Technical specifications
11	Dynamic Air Technology Inc [http://www.dairtech.net/products.htm]	D-MEC	Media Type Direct Evaporative Cooler Deep CELdek or GLASdek media Range from 2,500 cfm to 46,000 cfm and special units could be built up to 120,000 cfm
		D-IDC	Two Stage Inderct/Direct Eavaporative Cooler Deep CELdek or GLASdek media Range from 2,000 cfm to 30,000 cfm, and special units could be built up to 60,000 cfm
12	EcoCooling Ltd [http://www.ecocooling.co.uk]	ECPD/S/T	Direct Evaporative Cooling Cooling pads are Munters Celdek honeycomb, saturation efficiencies in the range of 85–89% Water: supply minimum 1 bar max 7 bar. Minimu supply 500 l/h Electrical supply: 240 V 50 Hz. 12A start 3A running
		ECP CREC	Direct Evaporative Cooling Nominal Air Flow Rate: 6,000–12,000 m^3/h
		ECPSDU	Direct Evaporative Cooling Each system requires a minimum of 4 m^3/s ventilation to maintain efficiency and performance Water flow rate: minimum 500 l/h
		ECM	Direct Evaporative Cooling Producing a flow rate of up to 7,000 m3/h Designed to meet all European electrical, water and other safety legislation Cooling pads are Munters Celdek honeycomb, saturation efficiencies in the range of 85–89% Single phase, two speed 700 W motor
		ECPWB Wetbox	Direct Evaporative Cooling Nominal pressure Drop and Maximum Flow Rate: (1) Down and Top Discharge: 52 pa and 14,400 maximum flow rate; (2) Side Discharge: 52 Pa and 10,800 cum/h maximum flow rate Electrical supply: 240 V 50 Hz. 3A running Water: supply mini. 1 bar/max. 7 bar. Mini supply 500 l/h
12	Sierra Fresh Air Systems [http://www.sierra-fas.com/efficient_outdoor_air_products.asp]	EVAP Evaporative Cooling System series (ZEC130 and ZEC210)	Single-stage Direct Evaporative Cooling cfm RANGE: 11,000–14,000 (ZEC130), 15,000–23,000 (ZEC210) NOMINAL COOLING EFFICIENCY RANGE: 87.0–88.0% (ZEC130), 86.0–89.5% (ZEC210)
		EVAP Indirect/Direct Evaporative Cooling System - Model Aztec (ASC-5 to ASC-75)	Multi-stage rooftop evaporative cooling system cfm RANGE: 1,500–37,500 NOMINAL COOLING EFFICIENCY: Indirect Only—75%, Indirect/Direct - 110–118% AVAILABLE ARRANGEMENTS: Horizontal
13	Norman S. Wright/Airelink Mechanical [http://www.nsw-airelink.com/index_choice.htm]	Rooftop Ducted Evaporative Coolers (ES/ED330 to ES/ED 630)	Direct Evaporative Coolinig Performance capabilities of 1,900 cfm to 4,900 cfm Cooling power: 1/3–3/4 HP Input power: 1,008–1,440 W
		Commercial/Industrial Evaporative Coolers (ED/ES830, ED/ES213 and ED/ES143)	Direct Evaporative Coolinig Capacities up to 21,000 cfm Cooling power: 0.75–7.5 W Input power: 1,426–4,416 W Water usage: 28–96 GPH, Based on 40°F wet bulb depression (Includes Bleed-off)
14	Aolan(Fujian) Industry Co., Ltd[http://www.aolan-china.com]	Mobile Series (AZL008 to AZL035)/ Windows unit/Windows series (AZL16 to AZL50)	Direct evaporative cooling Airflow: 800–6,000/4,000–7,000/16,000–50,000 m3/h Output cooling power: 0.02–0.55/0.06–0.25/0.37–13 kW
15	XinJiang Green Refreshing Agel Air Environment Co. Ltd [http://www.cnlssz.com/product/]	Indirect evaporative water chiller Series (SZHJ-S-I-1 and SZHJ-S-I-2)	Chilled water flow rate: 20–120 t/h (SZHJ-S-I-1), 13–78 t/h (SZHJ-S-I-2) Maximum cooling ability: 115–690 kW (SZHJ-S-I-1), 150–900 kW (SZHJ-S-I-2) Maximum allowable temperature difference between supply and return water: 5° (SZHJ-S-I-1), 10 °C(SZHJ-S-I-2) Fan power consumption: 5.5–22.5 kW(SZHJ-S-I-1), 6.25–25.8 kW(SZHJ-S-I-2)
		Ceiling Multi-stage IEC Air Handler Series (Model 02 to 10), Cooling only	Air flow rate: 2,000–10,000 m^3/h Fan power consumption: 0.8–3 kW Evaporation efficiency of DEC section: 0–90% Water usage: 12–60 kg/h
		Horizontal Multi-stage IEC Air Handler Series (Model 02 to 60), Cooling only	Air flow rate: 2,000–60,000 m^3/h Fan power consumption: 0.8–30 kW Evaporation efficiency of DEC section: 0–90% Water usage: 12–360 kg/h

Table 3
The selected engineering project using IEC/DEC technologies.

No	Project information
1	**Project:** Evaluation of an OASys Indirect-Direct Evaporative Cooler Retrofit [http://www.speakmancompany.com/files/15971] **Product Supplier:** Speakman CRS **Project profile:** Installed at 2006 in a Sacramento area PATH demonstration house. Before the OASys installation, the 43-year old house was air-conditioned exclusively using a 5-ton AC system. The house also included an existing (but no longer functional) roof mounted evaporative cooler. SWA evaluated the drop-in replacement of the existing evaporative cooler with the OASys, interviewing the HVAC contractor and homeowner and installing long term monitoring equipment in order to quantify: OASys and AC energy use OASys cooling capacity over a range of outdoor conditions Indoor house temperature and relative humidity This evaluation effort was co-funded through the Building America Program and the Sacramento Municipal Utility District (SMUD). Results indicate that (1) The cooling capacity of the OASys is comparable to that of a typical 2-ton AC system and (2) The Energy Efficiency Ratio (EER) of the OASys is roughly 3 times greater than that of a SEER 14 AC system.
2	**Project:** Evaporative Cooling for Badwater, California [http://www.munters.us/upload/Related%20product%20files/Evaporative%20Cooling%20for%20Badwater%20CA%20Case%20Study.pdf] **Product Supplier:** Munters **Project profile:** To meet ventilation requirements of the 2001 California Title 24 Energy Code as well as ASHRAE Standard 62-2001 both called for a minimum outdoor air quantity of 1.5 cfm per square foot of auto shop floor space, a total outdoor air requirement of 18,000 cfm for the two shops is needed. With California's severe energy shortages in 2001, the decision was made to use an Indirect/Direct Evaporative Cooling Unit (IDEC) design rather than refrigeration. On a 121°F design day, the two-stage evaporative cooling systems would deliver 68°F to the conditioned space, allowing the indoor temperature to be maintained at 85°F or lower while introducing the code required outdoor air quantity. This system would consume only 0.2 kW per ton (kw/ton) of electrical energy for sensible cooling of the space compared to the more conventional air-cooled refrigeration design which would require 1.2 kW/ton or worse at the higher ambient dry-bulb conditions. Till October 8, 2005, the IEC/DEC equipment had completed three years of operation. It was noticed that the cadmium plated bolts had deteriorated to the point that they crumbled as they were removed. After the panels were removed it was also determined that the sump pump and the metal box surrounding the pump had considerable hardness deposits on the surfaces. the scavanger side of the ABS plastic tubes were free of harmful deposits the remainder of the equipment was clean and in like new condition the equipment was operating as intended, delivering the cfm and temperature as specified.
3	**Project:** The Cooling of Green House Data [http://www.coolerado.com/products-files/2011/casestudies/casestudy_greenhousedata.pdf] **Product Supplier:** Coolerado **Project profile:** Green House Data—a 100% wind powered data center in Cheyenne, Wyoming—began its business in 2008 with the mission to build a super-energy-efficient client server and data storage system. Like every data center, Green House Data which was 2000 square footage with an upcoming add of 3,000 needed a reliable air conditioning system that would cool its server room 24 h a day, seven days a week—without fail. Traditional cooling methods would have taken an enormous amount of energy throughout the year. By using 14 Coolerado M50's, in two years, Green House Data had reduced its cooling bill by 90% and had experienced an overall total energy reduction in the data center of 40%. Besides providing Green House Data with a dramatic reduction in energy savings and an increase in sustainability, Coolerado also met the company's reliability needs. In addition, the modular installation system provided a critical backup option, so if an air conditioner needed to be taken offline, it wouldn't impact the servers or operation.
4	**Project:** Application of Dew Point Indirect Evaporative Cool Technique in Textile Mill [Du Lei. Application of Dew Point Indirect Evaporative Cool Technique in Textile Mill. Progress in Textile Science & Technology. 2009, No. 3: 50–52] **Product Supplier:** Unavailable **Project profile:** As pre-cooling, combined with mechanical cooling system, the dew point indirect evaporative cooling technique was adopted in by a textile mill with 1200 m^2 in Shaoxing of Zhejiang province China. Through test and calculating, the dew point indirect evaporative cooling section could lower temperature 6–8 °C and maintain room relative humidity between 70–85%. Complete fresh air could improve workshop air quality; the use of hybrid system could save energy 14% comparing to simple mechanism refrigeration air conditioning.
5	**Project:** Three Stages Evaporative Cooling in a functional building located in Karamay of Xinjiang Province China [Huang Xiang, Qu Yuan and Di Yuhui. Application of multi-stage evaporative cooling air conditioning system to northwest China. HV & AC. 2004, Vol. 34, No.6: 67–71] **Product Supplier:** XinJiang Green Refreshing Agel Air Environment Co. Ltd **Project profile:** General information of this hospital building: (a) Floor No: 13 in total; (b) Area: 2,000 m^2; (c) Room type: Lecture room and lounge hall Air conditioning system: (a) Model: SZHJ-III-50; (b) 3 stages evaporative air conditioning system (IEC+IEC+DEC); (c) Air flow rate: 5000 m^3/h; (d) Design sensible cooling load: 700 kW;(e) Date of start in operation: July 2001 Operation performance test and conclusions Time: 15:52–17:54 Date: 12/August/2001 Test results: outdoor air 36 °C db/20 °C wb; supply air: 15.5 °C db/14.5 °C wb
6	**Project:** Indirect-Direct Evaporative Cooling at McCarran Airport, Las Vegas Nevada [http://www.swenergy.org/events/evaporative/Summary.pdf] **Product Supplier:** Des Champs Technologies **Project profile:** Des Champs Technologies developed an indirect evaporative cooling system for the McCarran Airport Terminal in Las Vegas, Nevada. The system consists of 15 Des Champs IDEC units ranging in size from 8,000 cfm to 28,000 cfm, for a total of 280,000 cfm of equipment. The IEC system uses an EPX polymer heat exchanger that resists mineral buildup, which is a major challenge to the use of evaporative cooling in Las Vegas because of hard water conditions. The Des Champs system provides cold supply air with an EER of 42, which is much more efficient than refrigeration based systems.
7	**Project:** Pharmaceutical Warehouse [http://www.ecocooling.ie/casestudies.pdf] **Product Supplier:** Ecocooling **Project profile:** Merck Sante, based in the French city of Orleans, manufactures and distributes pharmaceutical products. Their main warehouse is required to operate under the conditions of 'controlled room temperature' which for their range of products is less than 250 °C. Eighteen down discharge EcoCooling

Table 3 (*continued*)

No	Project information
	ECP16000 evaporative coolers were installed feeding high level plenum chambers. These positively pressurize the warehouse and air is extracted using automatic vents. The coolers are all linked to a common control panel. Temperature is monitored at three levels in the warehouse and the coolers controlled accordingly. A humidistat ensures that the internal humidity does not exceed 85%. The principle of mean kinetic temperature can be applied to pharmaceutical storage using the Arrhenius Equation. The graph opposite shows that on a 40 °C day the ambient MKT is 33 °C. The output of an evaporative cooler in these conditions gives a MKT of 25 °C which meets the storage criteria for this range of pharmaceutical products.
8	**Project:** Roxby Downs Leisure Centre [http://climatewizard.com.au/en/case-studies-and-testimonials] **Product Supplier:** Seeley International Pty Ltd **Project profile:** Roxby Downs Leisure Centre is located at BHP Billiton Roxby Downs Village, South Australia. The task is to provide low energy consumption cooling to the leisure center complex. The complex has a limited power supply capacity, so any solution had to be very efficient, but still provide full comfort when the center is fully occupied. Twelve Climate Wizard air conditioners were installed under the main roof, within the plant room and connected to a manifold and ducts to each zone. A building management system (BMS) provides flexibility of control and zone selection. In normal operation, the system operates at a coefficient of performance (COP) of around 20 (EER 68.4), compared to the originally proposed alternative refrigerated system, which had a COP of about 3.2 (EER 10.3).
9	**Project:** Martin-Baker Aircraft Company [http://www.evaporativecoolingsystems.co.uk/case-studies.html] **Product Supplier:** Aircon Services **Project profile:** *Company*—Martin-Baker Aircraft Company were experiencing temperatures of up to 40° centigrade in various buildings at their Denham manufacturing site, and were also looking to improve their electrical efficiency. The company has a 22 acre site, making ejection seats and aviator survival equipment. *Objective*—To cool various departments such as Auto Anodising, None Destructive Tests (NDT), the Kitchen (43° centigrade), Sewing Room, Parachute Packing and Offices. All the departments required different approaches for the provision of 'Cooled' air. *Task*—We installed Evaporative Cooling and Extraction systems. This generated 100% fresh, filtered air, healthier working conditions and around 80% savings on conventional air conditioning. We fitted each department with a different air supply, with simple Ducts, specialized Plenums, Polymer Grilles, and bespoke Ventilation Socks. *Result*–All departments were cooled to around 21° centigrade, including the Kitchen. The Ventilation 'Socks' provided cooled air virtually draft free.
10	**Project:** Hewland Engineering [http://www.cleanair.co.uk/news.php] **Product Supplier:** Clean Air Group **Project profile:** At the recommendation of an existing client, Hewland Engineering, Clean Air were asked to reduce the temperatures of their stores and machining areas. Twelve Cool Breeze QAD230 (DEC Type) units were fitted, alongside a pair of extract fans that compliment the existing passive roof ventilation units. Each Cool Breeze unit is individually controlled to provide different temperature zones between the areas. The results proved so impressive that the factory became a more comfortable environment than the large open plan offices. These were being cooled using an old water chiller that supplied numerous indoor fan coils. The result is not just a comfortable working environment and contented staff, but also energy savings of up to 80% and low maintenance costs.

into this type of system were reported in numerous literature sources [11,23,28–34].

From production point of view, several hundred of manufacturers are currently in operation across the world including several most prominent businesses e.g., Munters Group, Coolerado et al. Table 2 provides a list of global level IEC/DEC manufacturers and their production information.

From application point of view, larger quantity of building installations are found in hot and (or) arid climate regions such as Middle East, Asia and North American. Use of the IEC/DEC in mild climatic regions e.g., Europe, is still small in terms of its sale volume and number of building installations. Table 3 provides the information related to several most notable IEC/DEC engineering practices.

3. Basic concept and operational principle, performance evaluation methods/standards, system configuration and operational modes related to the IEC

3.1. Basic concept of the IEC and its operational principle

3.1.1. Conventional IEC systems

Indirect Evaporative Cooling (IEC) systems can lower air temperature without adding moisture into the air, making them the more attractive option over the direct ones. In an indirect evaporative air cooling system, the primary (product) air passes over the dry side of a plate, and the secondary (working) air passes over the opposite wet side. The wet side air absorbs heat from the dry side air with aid of water evaporation on the wet surface of the plate and thus cools the dry side air; while the latent heat of the vaporized water is transmitted into the working air in the wet side.

If the product air of the IEC system travels in a counter flow manner to the working air at an appropriate air-flow-ratio and across an infinite surface area, the temperature of the product air in the dry side of the plate will reach the wet-bulb temperature of the incoming working air. The temperature of the working air in the wet side of the plate will be lowered from its incoming dry-bulb temperature to the incoming wet-bulb temperature. However, the actual effect is that only 40–80% of the incoming air wet-bulb temperature can be achieved [20]. The reasons for the reduced cooling effectiveness are investigated, giving identification of several attributing facts: (1) there is limited heat-exchanging-surface area; (2) none pure counter flow pattern could be achievable; and (3) uniform and even water distribution over the wet sides of the plate is hard to obtain.

Fig. 3 presents the working principle and psychometric illustration of the air treatment process relating to an indirect evaporative cooling operation. During operation, the primary (product) air enters into the dry channel while the secondary (working) air enters into the adjacent wet channel. The primary air is cooled by the sensible heat transfer between the primary air and the plate, which is induced by the latent heat transfer relating to water evaporation from the plate's wet surface to secondary air. As a result, the primary air (state 1) is cooled at the constant moisture content and moves towards the wet-bulb temperature of the inlet secondary air; whereas the secondary air of sate 1 is gradually saturated and changed into state 2′ at its earlier flow path, then heated when moving along the flow path and finally discharged to atmosphere in the saturated state 3. It should be noted that to enable heat transfer between the dry side air to wet side air, the state 3 should have a lower temperature than the state 2 and theoretically speaking, the enthalpy decrease of the air within the dry side channel is equal to the enthalpy increase of the air within the wet side channel, i.e., $h_1-h_2=h_3-h_1$.

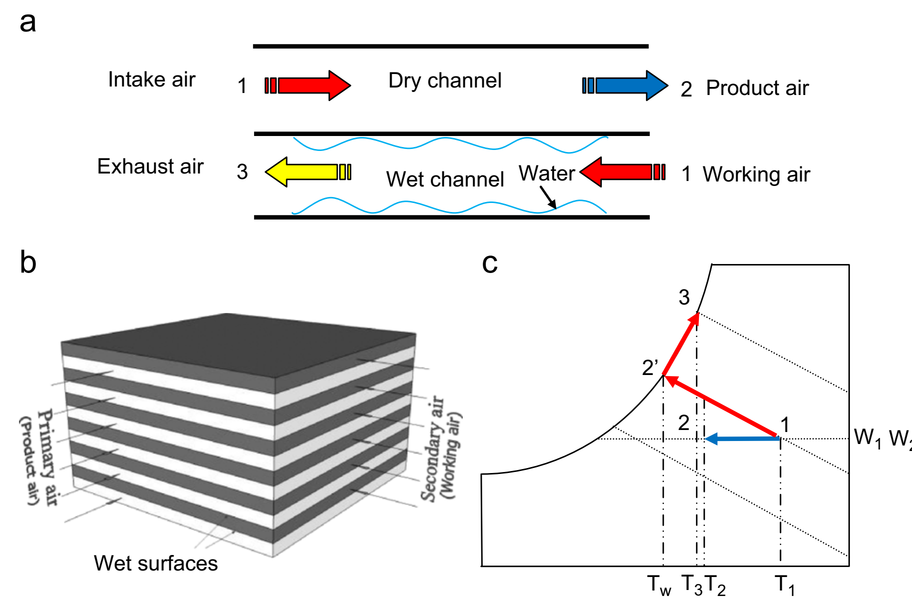


Fig. 3. Conventional IEC heat and mass exchanger. (a) Working principle of the indirect evaporative cooling, (b) Configuration of the type IEC heat and mass exchanger and (c) Psychrometric illustration of the air treatment process in the IEC heat and mass exchanger [24,28,30].

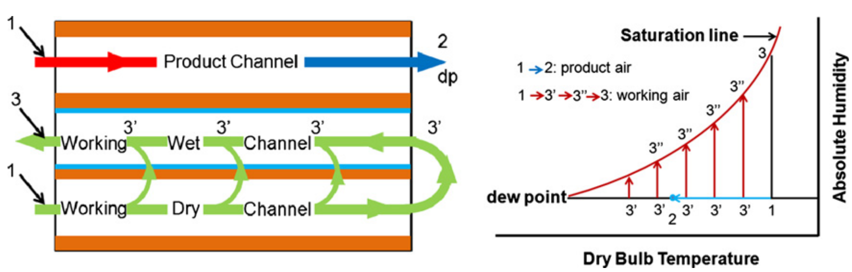


Fig. 4. Principle of the heat and mass exchanger based on M-cycle and its representation on psychrometric chart [33].

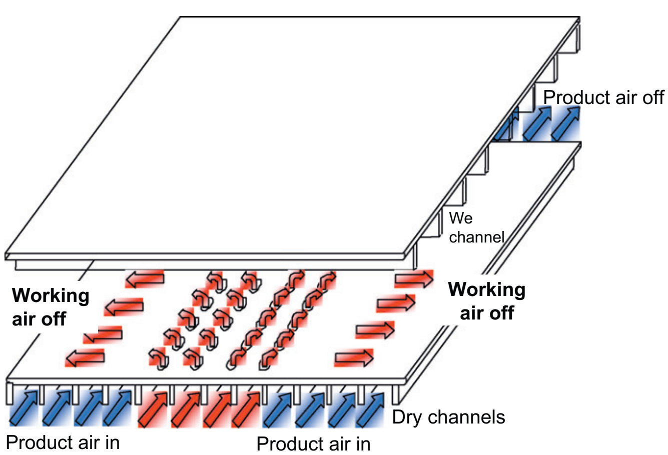


Fig. 5. Schematic of a heat and mass exchange module based on M-cycle [29].

3.1.2. *M-Cycle IEC systems*

To enhance cooling performance of the IEC heat exchanger, a novel thermodynamic cycle, known as the M-cycle [11,29,33], was proposed by Professor Valeriy Maisotenko as the new approach of making and operating a heat exchanger. This cycle was claimed to enable harnessing extra amount of energy from the ambient using a dedicated flat plate, cross-flow and perforated heat exchanger, as shown schematically in Figs. 4 and 5. During operation, all part of air is initially brought into the dry channels of the heat exchanger, and cooled when moving along the flow path owing to the established temperature difference between the dry and wet side of the exchanger plates. When passing across the perforated holes, part of the air, known as the 'working (or secondary) air', is diverted into the adjacent wet channels. Within the wet channels, the air travels in normal direction to the dry channel air, taking away the evaporated water from the saturated wet surface of the plate and receiving the sensible heat transferred across the plate. As a result, the working (secondary) air is gradually saturated and heated when travelling across the flow paths, and finally discharged to ambient, leading to the state change from point 3′, 3″ to 3. Meanwhile, the remaining air in the dry channel continues to move forward and at the end of its flow path, is cooled to a state below its relative wet bulb and close to its dew point. Compared to the conventional IEC heat exchanger, this M-cycle exchanger will produce a much colder airflow to be delivered to the room space, thus generating the increased cooling output. Due to its potential in reaching the dew point of the product air, the approach is also known as 'dew point (M-cycle) cooling'. A test indicated that the M-cycle based heat exchanger could obtain a wet bulb effectiveness of 81–91% and dew point effectiveness of 50–60% [29], which is 10–30% higher than that of the conventional IEC heat exchangers.

Although the M-cycle cross-flow heat exchanger has achieved distinctive increase in the cooling effectiveness relative to the conventional IEC heat exchanger, its operation is still facing several limitations: (1) the working air is not fully cooled as high proportion of it is gradually diverted into the adjacent wet channels early on in the flow path, and (2) the structure creates

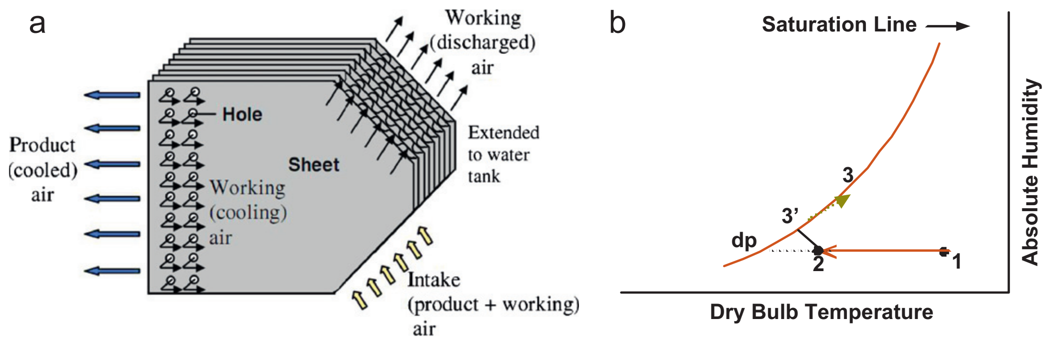


Fig. 6. Structure and operation of the M-cycle counter-flow heat exchanger for indirect evaporative cooling. (a) Structure illustration and (b) air treatment process—psychometric [30].

a cross air flow pattern that is unfavourable to heat exchanging. This limited its dew-point/wet-bulb cooling effectiveness to the level of around 50–60% and 80–90% [29], respectively. To further enhance the cooling effectiveness of the IEC systems, a M-cycle counter-flow heat exchanger was recently developed by the authors. The structure and operation of this type of exchanger is shown schematically in Fig. 6 [30]. Unlike the M-cycle cross-flow exchanger that has the perforated holes widely spreading across the flow paths, the new exchanger positions those holes to the end of the flow channels (end side of the exchanging sheet). During operation, both the product and working air are directed into the dry channels, losing heat to the adjacent wet channels and at the end of each channel, all parts of air are cooled to a level approaching the inlet air's dew point. At this end, part of the air (product air) is delivered to the building space and the remaining air (working air) is diverted to the adjacent wet channels, where it travels on an opposite direction to the dry channel air. Compared to the cross-flow heat exchanger, the M-cycle counter-flow heat exchanger was found several advantages: (1) the working air travels to the end of the dry channels and therefore could be fully cooled, leading to increased temperature difference and heat transfer between the two air streams, and (2) counter-air-flow pattern could be created to enable enhanced heat transfer between the product and working air streams. Both simulation and experiments indicated that the M-cycle counter-flow exchanger offered greater (around 20% higher) cooling capacity, and greater (15–23% higher) dew-point and wet-bulb effectiveness than the M-cycle cross-flow exchanger of the same physical size and under the same operating conditions [28].

3.2. Performance evaluation standards and indicative parameters

3.2.1. Standards overview

A review into standards relating to testing and rating of the IEC systems was conducted. No international IEC related standard was found to be in existence; however, numerous regional/national standards of this kind were well in place. The most well known IEC standards are (1) ANSI/ASHRAE Standards (133-2008/143-2007) [35,36] and California Appliance Efficiency Regulations (USA) [37]; (2) AS/NZS 2913-2000 (Australia) [38]; (3) Labeling Program (Iran) [39]; (4) IS 3315-1974 (India) [40]; (5) SASO35/36 (Saudi Arabia) [41,42]; (6) C22.2 No 104 (Canada) [43]; and (7) GB/T 25860-2010 (China) [44].

ANSI/ASHRAE Standard 133-2008 provided the method applicable to USA for testing of Direct Evaporative Air Coolers, which contained detailed instruction to measurement of the IEC operational parameters i.e., cooling (saturation) effectiveness, airflow rate, power, COP, pressure drop, air density and fan rotation speed etc. On this basis, ANSI/ASHRAE Standard 143-2007 made further amendment to the approach of rating the Indirect Evaporative Coolers, taking into account flow rates and dry/wet bulb temperatures of the primary/secondary airstreams. To enable quantitative measure of the IEC performance, California Appliance Efficiency Regulations defined a new parameter namely 'Evaporative Cooler Efficiency Ratio', which is the ratio of the cooling delivery volume to electrical power needed for an IEC under the specific lab-controlled operational condition.

In Australia, AS/NZS 2913-2000 is the sole standard applicable to evaluation of the performance of the DEC and IEC systems. This standard provided method for measuring the most important parameters including dry/wet bulb temperature, air flow rate, evaporation efficiency, and electrical consumption, and indicated that the measurement should be undertaken at the controlled inlet air condition, i.e., 38 °C inlet air dry bulb, 20 °C inlet air wet bulb, and 27.4 °C room temperature. In this document, no water consumption was addressed and the multi-stage systems were not given consideration.

In Iran, the labelling system was applied to assess the performance of the evaporative air coolers. This system, adopting the European concept, divided the cooling units into 7 grades in terms of the energy efficiency: grade 1 is most energy efficient, represented by the shortest, green colour bar, while the grade 7 is the least energy efficient with presence of longest, red colour bar. This system, released in 1999 with the aim of encouraging promotion of energy efficiency of the IEC and DEC products, has become the first of this kind method guiding the testing and rating process of the evaporative cooling products. To enable comparison of the efficiency of different evaporative coolers with the same rated cfm, the EER (Energy Efficiency Ratio) was used as the unit to assess energy efficiency. This energy label, viewed as a useful marketing tool, has now been widely accepted by Iran's IEC and DEC manufacturers. It was addressed that all tests should comply with the Iranian Test Standards No. 4910 and No. 4911, which is viewed as the equivalent issue to the Australia Standard 2913-2000. Again, no water consumption was addressed in this document.

IS3315, initially published in 1974 and later updated in 1991 by the BIS Bureau of Indian Standards, is the sole standard used in India to guide the testing and rating processes of the evaporative air coolers. In Saudi Arabia where climates are at hot and arid state, use of evaporative cooling has been the common practice as part of building air conditioning measures. To meet the requirement of design, production and installation of the IEC and DEC products, SASO 35 and 36 were published in 1997 by Saudi Arabian Standards Organisation (SASO) and treated as the guidance towards the measurement and rating of the IEC and DEC products. In Canada, C22.2 No 104: Humidifiers and Evaporative Coolers, was developed and published in 1983, and updated in 1989 by CSA International.

In China, the first IEC/DEC standard namely, GB/T 25860-2010 Evaporative Air Cooler, was developed in 2010. This standard addressed various issues related to the IEC/DEC including terms, definitions, types, requirements, testing procedures, signs, packaging, transportation and storage. It is considered as the legal document applicable to the IEC/DEC related productions and building installations.

3.2.2. Indicative parameters

Review of the IEC/DEC standards indicated that the performance of an IEC system could be represented by several characteristic parameters including (1) wet-bulb or dew point effectiveness; (2) evaporative cooler efficiency ratio; (3) cooling capacity; (4) power consumption; (5) energy efficiency; (6) water evaporation rate; (7) secondary-to-primary air ratio; (8) pressure loss; and (9) air flow rate. These are detailed as follows:

(1) **Wet-bulb (dew-point) effectiveness**

Wet-bulb effectiveness is a parameter describing the extent of the approach of the outlet product air temperature of the IEC against the wet-bulb temperature of the inlet working air, and can be written as:

$$\varepsilon_{wb} = \frac{t_{p,db,in} - t_{p,db,out}}{t_{p,db,in} - t_{p,wb,in}} \tag{1}$$

Dew point effectiveness is another parameter used for this purpose and defined as the ratio of the temperature difference between the inlet and outlet product air to the difference between the inlet product air's dry bulb and inlet working air's dew point temperature. This reflects the extent of the approach of the outlet product air temperature against the dew point temperature of the inlet working air related to the IEC, shown as follows:

$$\varepsilon_{dp} = \frac{t_{p,db,in} - t_{p,db,out}}{t_{p,db,in} - t_{p,db,in}} \tag{2}$$

It should be addressed that the dew point effectiveness is particularly suitable for use in recently emerging dew point system, an innovative form of IEC configuration.

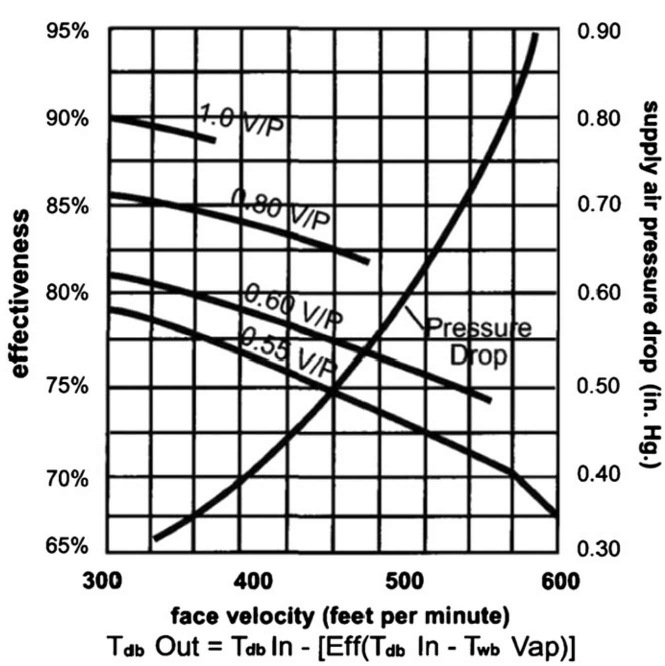


Fig. 7. Wet-bulb effectiveness—Performance chart of IEC [46].

The standard and M-cycle IEC systems could achieve wet bulb effectiveness of 50–80% and 80–90%, respectively. It is understood that the wet-bulb (dew point) cooling effectiveness of the IEC systems are the issues in relation to the geometrical and operational conditions of the IEC heat exchanger, particularly uniformity of water and air distribution across the channels and heat transfer surface [22,29,30,45,46]. Fig. 7 presents the relationship between the wet-bulb effectiveness and associated operational parameters [46]. The wet-bulb effectiveness of the IEC is found to decrease with increasing air velocity and decreasing the secondary-to-primary air ratio, while the pressure drop increases with increasing the air velocity.

(2) **Evaporative cooler efficiency ratio (ECER)**

ECER, defined as the ratio of the cooling delivery volume to electrical power related to the IEC, is measured on the condition of intake air dry/wet bulb temperature of 32.8/20.6 °C and room air temperature of 26.7 °C. This could be expressed in the following equation:

$$\text{ECER} = \rho_f c_f \left[t_{room} - \left(t_{p,db,in} - \varepsilon \left(t_{p,db,in} - t_{p,wb,in} \right) \right) \right] V_{p,out} / W \tag{3}$$

(3) **Cooling capacity**

The cooling capacity refers to the enthalpy change of the product air when travelling across the dry channels of the IEC heat exchanger, and is expressed as follows:

$$Q_{total} = \rho_f V_{p,out} \left(i_{p,db,in} - i_{p,db,out} \right) \tag{4}$$

Since the air is cooled at the constant moisture content during the dry channels of the IEC exchanger, the enthalpy change of the air could be represented by the temperature reduction of the air during its dry channel flow path. For this reason, the above equation could be rewritten as:

$$Q = c_f \rho_f V_{p,out} \left(t_{p,db,in} - t_{p,db,out} \right) \tag{5}$$

(4) **Power consumption**

An IEC system consumes much less electrical power than conventional mechanical compression refrigeration based air conditioning systems. Unlike the conventional systems that use electricity to drive energy intensive compressor, and fan/pump, an IEC system uses electrical power to drive fan and pump only. In this system, the electrical power is measured by the unit of W or kW.

(5) **Energy efficiency**

Energy efficiency, known as 'coefficient of performance (COP), is the ratio of the cooling capacity of the IEC to the power consumption of the system. This term can be mathematically expressed as:

$$\text{Energy efficiency} = \frac{Q}{W} = \frac{c_f \rho_f V_{p,\text{out}} \left(t_{p,db,\text{in}} - t_{p,db,\text{out}} \right)}{W} \tag{6}$$

If this figure is multiplied by a unit conversion factor of 3.413, the COP is then converted into the energy efficiency ratio (EER). It is known that the EER of an IEC system is usually in the range 30–80 [28,29,47].

(6) **Water evaporation rate**

The water evaporation rate of an IEC system depends upon a number of its operational parameters, e.g., the inlet air temperature/humidity, airflow rate, treated cooling load, as well as the system's cooling effectiveness. Theoretically speaking, the water evaporation rate is equal to the volume of the moisture increase in the working air during its indirect cooling operation

and could be expressed as:

$$V_w = \frac{V_{s,out}\rho_{s,f}}{\rho_w}(w_{s,out} - w_{s,in}) \tag{7}$$

(7) **Secondary-to-primary air ratio**
In an IEC system, the secondary air, known as the 'working air' is used to cool the primary (i.e., product) air. Ratio of the secondary to primary air-flow is an important measure effecting on the cooling performance of the system. It is claimed that the ratio of the secondary to primary air is usually in the range 0.3–1.0 [29,34,46,47] and during operation, increasing the value of this ratio will lead to increase of the cooling effectiveness. However, this increase will also lead to reduced supply air volume and thus the overall cooling capacity of the system may fall. There will be an optimised figure on the ratio that will enable the maximised cooling capacity of the system and adequate cooling effectiveness. This figure will be determined using the dedicated computer programme under a given geometrical and operational conditions.

(8) **Pressure loss**
Pressure loss refers to static pressure drop of the air when passing across the dry and wet channels of an IEC heat exchanger. In a typical heat exchanger for indirect evaporative cooling, the static pressure drops of the air in dry and wet channels is found to be in the range 60–185 Pa and 100–500 Pa, respectively [13,46].

(9) **Air flow rate**
Air flow rate refers to air volume flow rate across the IEC heat exchanger channels including dry and wet channels. The air flow rate is usually measured by the unit of m^3/s or m^3/h.

3.2.3. Summary of the IEC parametric performance

To summarise, an indirect evaporative cooling system is found to be able to achieve 40–90% of wet bulb effectiveness, depending on the inlet air condition, system structural configuration and geometrical size, ratio of the working to product air, and air velocity across the heat exchanger channels. In a typical IEC heat and mass exchanger, the static pressure drops of the air in dry and wet channels is in the range 60–185 Pa and 100–500 Pa, respectively; while the ratio of the working to product air varies from 0.3–1, and the system's cooling energy efficiency ratio (EER) falls to the range between 30 and 80. Table 4 provides the parametric data of the selected heat and mass exchangers for indirect evaporative cooling.

3.3. System configuration and operational mode

3.3.1. System configuration

The commonly available heat and mass exchanger for IEC operation is in form of the flat-plate-stack, which could create either cross- or counter- flow pattern and through different perforating treatments, the working air could be drawn into the wet channels by either directly from outside or from the adjacent dry channels, thus creating different cooling effectiveness in the range 0.4–0.9. This type of exchanger is shown schematically in Figs. 3, 5 and 6. In the heat exchanger, water enters into the wet channels from the top. This type of heat exchanger can cool the primary air down to 40–90% of wet-bulb of the inlet secondary air, has the static pressure loss of 60–185 Pa at the dry channels, 100–500 Pa at the wet channels, keeps the secondary-to-primary air ratio in a range 0.3–1, and obtains the energy efficiency ratio (EER) between 30 and 80.

Apart from the flat-plate-stack structure, the IEC heat exchanger could also be configured as tube, heat pipe, rotary wheel and tube forms, which are illustrated as follow:

Table 4
Summary of the parametric data relating to the selected IEC plate heat exchangers.

Parameters	Unit	Alonso [19]	Stoitchkov [20]	Guo [47]	Zhan [28], Qiu [22]	Elberling [29]	Riangvilaikul [24]
Flow pattern		Cross-flow	Cross-flow	Cross-flow	M-cycle cross-flow	M-cycle cross-flow	M-cycle Counter-flow
Primary air inlet db temp	°C	35–45	24–36	25–45	25–40	26.7–43.8	25–45
Primary air inlet wb temp	°C	19.5–23.3	17.7–28.3	N/A	17.9–30.3	18.1–23.9	10.7–32.5
Secondary air inlet db temp	°C	23.5–27.2	22–28	25.0	N/A	N/A	N/A
Secondary air inlet wb temp	°C	16.8–18.6	16–21	11.4–23.8	N/A	N/A	N/A
Primary air velocity/flow rate		0.022 m^3/s	3.3 m/s	0.5–4.5 m/s	0.036 m^3/s	0.53–1.38 m^3/s	2.4 m/s
Secondary to primary air ratio		0.5	0.5	0.5–2	0.5	0.5	0.33
Primary Channel length	m	0.3	0.4–0.7	0.2	0.25	N/A	1.2
Channel gap	mm	3.0	3.5	2–10	4	N/A	5
Product air db temp	°C	20.8–24.8	17.2–23.6	21.3–26.3	18–30	19.9–25.6	15.6–32.1
Wet-bulb effectiveness		0.77–0.93	0.79–0.88	0.78–0.95	0.5–0.65	0.81–0.91	0.92–1.14

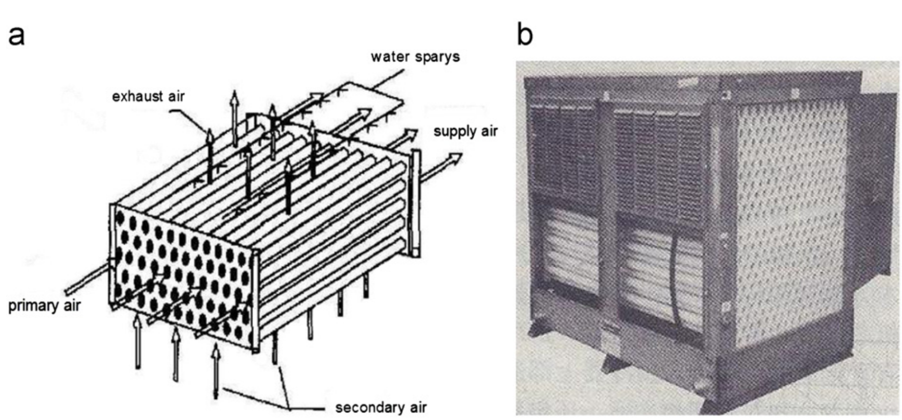


Fig. 8. IEC Tube heat exchanger: (a) work diagram of tube heat exchanger and (b) tube heat exchanger product [48].

(1) **Tube structured IEC systems**

Fig. 8 presents a tube-based IEC heat exchanger invented by Velasco Gomez et al. [48]. This structure allows the primary air to flow through the internal tubing space on its length direction, and the second air to sweep across the external surface of the tubes in the normal direction to the primary air. Meanwhile, the water is sprayed over the external surface of the tubes from the top. This exchanger is claimed to be able to obtain more uniform water films on the outer surface of the tubes and thus reduced air flow resistance than the flat-plate-stack structure.

In this structure, the tubes are made of either polymer, metal, porous ceramic, or PVC. Over the recent years, the hydrophilic aluminium tubes with wall thickness of 0.02–0.06 mm were gradually applied in this process owing to their several distinctive advantages, e.g., high thermal conductivity, low cost, and capability of forming the uniform water film. The new approach for treating the aluminium tubes was to wrap a thin layer of water affinity material (e.g., cotton, polyester fibre, special fibre, metallic wick, stainless steel mesh) to the outer surface of the tubes [44], which has been proven to be effective in improving its water uniformity over the surface and thus enhancing the cooling effectiveness of the IEC. Porous ceramics, owing to the large specific surface area, excellent water retaining capacity and superior mechanical strength, were also found to be the favourite materials for making tubes. During this process, a non-permeable membrane is normally attached to the inner surface of the porous ceramic tubes to prevent moisture transfer across the tube walls.

The second tube-based IEC heat exchanger is shown schematically in Fig. 9 [48]. In this structure, the primary air sweeps across the outer surface of the tubes while the secondary air flows through the inner space of the tubes. The wall of the tubes, made of the thin porous layer, is designed to retain the spray water which helps transfer heat between the primary and secondary airstreams, through evaporation of water reserved in the porous media. The diffusion of the water from the pores to the air depends upon the permeability of the porous wall. This structure is claimed to be able to obtain an improved cooling effectiveness over the one in Fig. 8 and its wet-bulb effectiveness is in the range 40–80%.

(2) **Heat pipe based IEC system**

Heat pipe, as an effective heat transfer device with considerable thermal conductivity, can be applied to transport heat from the primary to secondary air. A schematic of such a heat-pipe based IEC configuration is shown in Fig. 10 [49]. The heat pipe is divided into hot (condenser) and cold (evaporator) parts separated by thermal insulator. By using the latent heat of evaporation and the capillary action of wick material filmed on the inside wall of heat pipe, the internal working fluid is circulated between hot and cold parts. The hot part acts as the evaporator whilst the cold part as the condenser. There is a thermal insulator to connect two insulation enclosures to minimize heat transfer between the hot and cold parts from the external surface of heat pipe. In operation, the secondary air is heated when passing through the condenser of the heat pipe where water (delivered by water sprayer) is evaporated on the external surface.

The heat pipe incorporated IEC can be combined with a direct evaporative cooler or/and chill water coil to form a hybrid system, as shown schematically in Fig. 11 [49]. Within such a hybrid system, the configuration of heat pipe can be any type from thermosyphon, leading edge, rotating and revolving, cryogenic, flat plate and capillary pumped loop heat pipe [50].

For the application indicated in Ref. [49], a cooling effectiveness of 70.39% could be achieved; this created up to 9.01 °C of temperature difference between the air and heat pipe wall at the primary air side and 12.3 °C of temperature difference between the air and heat pipe wall at the secondary air side. Compared to the flat-plate heat exchanger, the heat pipe is more suitable for larger airflow application owing to its relatively larger geometrical sizes. ASHRAE Handbook HVAC Systems and Equipment (2008) carried out the design and performance evaluation of a large sized heat pipe IEC system which is able to provide 23.6 m^3/s supply air and 775 kW cooling capacity. An available indirect evaporative cooler configured with the heat pipes was reported in [51], which indicated that 28% of power reduction could be achieved by using this device relative to the conventional mechanical air conditioning system with the same cooling capacity. Ref. [52] addressed the advantages and disadvantages of the application of

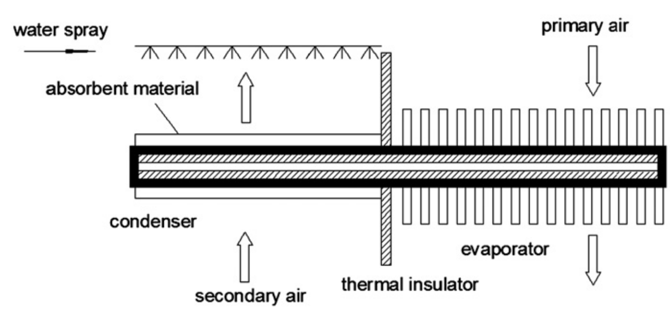


Fig. 10. Schematic of the indirect evaporative cooler with heat pipe configuration [49].

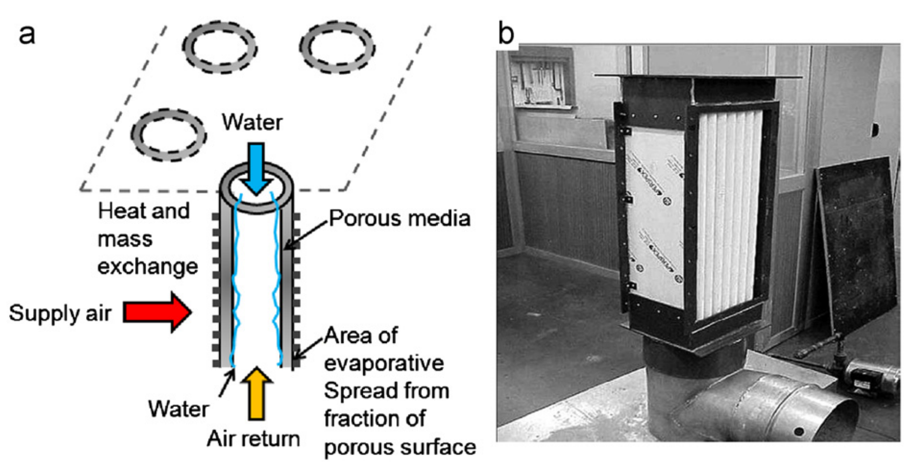


Fig. 9. Porous ceramic pipes semi-indirect evaporative cooler: (a) work principle of heat and mass transfer and (b) experimental prototype [48].

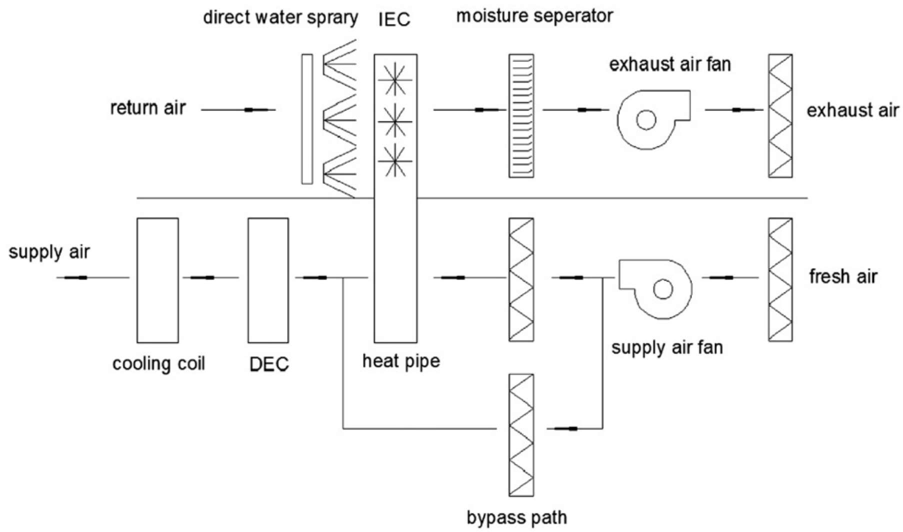


Fig. 11. Schematic of an indirect evaporative cooling system with heat pipe/DEC/chill water coil [49].

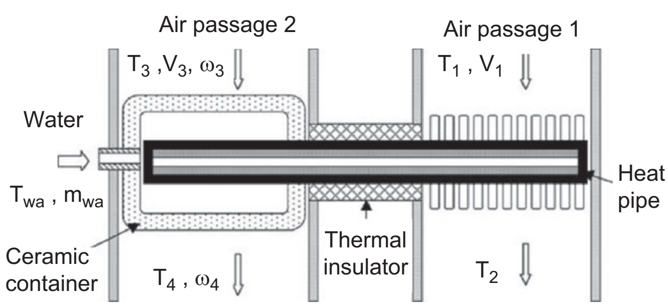


Fig. 12. Schematic of heat pipe IEC with porous ceramic container [44].

a heat pipe and wet medium incorporated air handling unit for building air conditioning operation.

A new type of heat pipe incorporated IEC with a porous ceramic container is shown schematically in Fig. 12 [44]. Unlike the water distributor shown in Fig. 10, a porous ceramic container, acting as water storage, is fitted into the hot end of the heat pipe, which can distribute water more evenly than the typical water sprayer. A fin-structure, designed to increase convective heat transfer between the passing air and the heat pipe, can be fitted into both the evaporator and condenser sections. This combined heat pipe and porous ceramic system can achieve 30% higher efficiency than the typical heat pipe IEC system, whilst its water consumption is also smaller [49].

(3) **IEC/Cooling Tower/Coil Systems**
Jiang and Xie [45] developed an indirect evaporative chiller which can produce the chill water with the temperature below the wet-bulb and above the dew point of the outdoor air. The psychometric description of the air-to-water cooling process is shown schematically in Fig. 13. The chiller comprises two parts, i.e., the air-to-water counter-current heat exchanger and the air-to-water counter-current padding tower. The first prototype chiller was constructed and installed in Xingjiang Province of China, in which a relatively lower ambient wet-bulb and dew point temperature is in presence. The long-term testing indicated that the unit can produce 14 to 20 °C of chill water, which is above the dew-point and below the wet-bulb of the outdoor air at summer. The system had COP of around 9, and could obtain over 40% saving in electrical energy consumption relative to the same sized conventional mechanical compression refrigeration based chiller.

3.3.2. Operational mode

An indirect evaporative cooling (IEC) system was found several inherent difficulties: (1) relatively lower cooling effectiveness; (2) smaller temperature reduction potential; (3) larger geometrical sizes; and (4) higher dependency to the ambient condition. These difficulties limited its wide application in buildings and to enable sufficient cooling output and stabilize the inlet air condition, an IEC system was usually not working independently; instead, it was always in joint operation with other cooling devices. The commonly used operational modes for the combined system are: (1) indirect/direct evaporative cooling (IEC/DEC) mode; (2) IEC/cooling coil or direct-expansion (DX) refrigeration system; (3) IEC/DEC/cooling coil or direct expansion refrigeration system; and (4) Desiccant/IEC/DEC System. These operations are detailed as follows:

(1) **Indirect/direct evaporative cooler (IEC/DEC)**
For this mode of operation, the direct cooling unit (usually the evaporative cooling pad) was positioned to the downstream side of the indirect cooling unit in order to further cool the primary air coming from the IEC. Fig. 14 presents the general layout of such a system and associated psychometric illustration of the air treatment process. In this system, outdoor air (state 1) was cooled at dry state condition in the IEC unit (to state 2) by using the return air as the coolant (secondary air) and further cooled and humidified in the downstream DEC unit, thus generating near to saturated low temperature air (represented by state 3) that was delivered to room space to conduct cooling for the served space. During this process, the secondary-to-primary air ratio varied from 0.3 to 1.0. This combined operation will lead to an enhanced cooling effectiveness in the range 70–110%, COP for cooling of 14.35, and more than 22% of electricity saving over the equivalent conventional mechanical vapour compression refrigeration based air conditioning systems [23,26,27].

(2) **IEC/cooling coil (with chilled water or refrigerant) system**
An IEC unit could be operated in conjunction with a cooling coil (or a direct-expansion (DX) refrigerant coil) to enable energy efficient air conditioning for buildings. A schematic of such a system is shown in Fig. 15(a) and associated psychometric

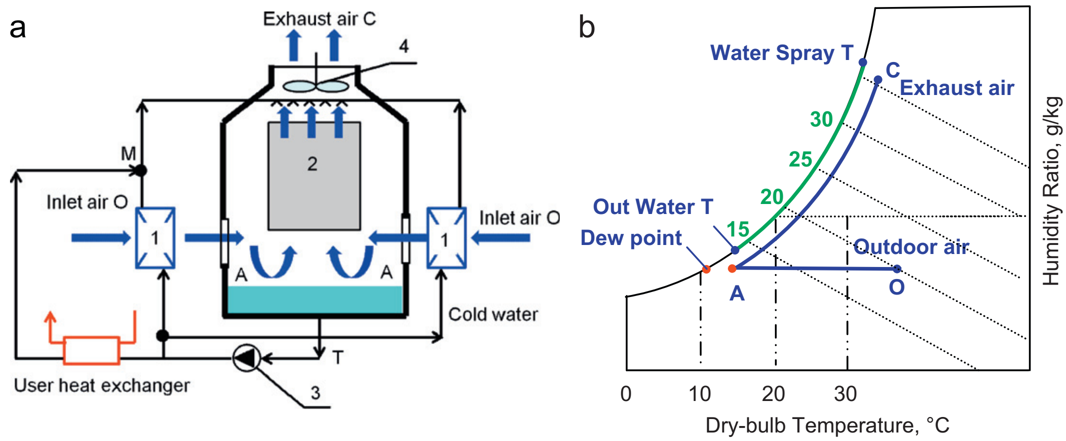


Fig. 13. Principle of the indirect evaporative chiller: (a) structure of the indirect evaporative chiller, (b) process to produce cold water. (1) air-to-water counter-flow heat exchanger; (2) air-to-water counter-flow padding tower; (3) water circulating pump; (4) exhaust fan [45].

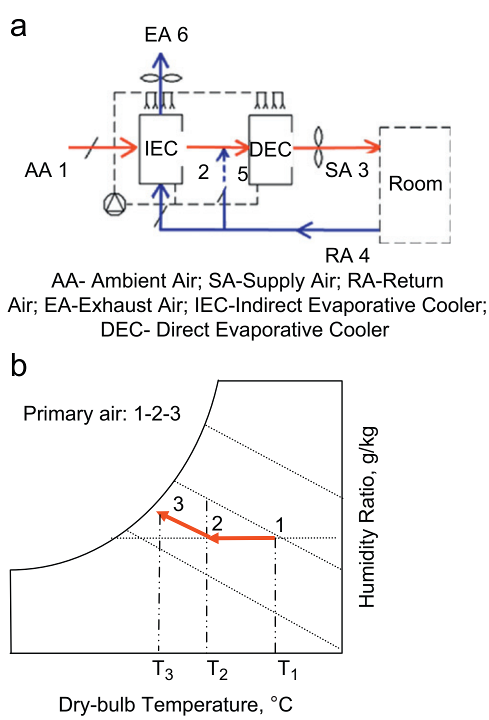


Fig. 14. Two-stage IEC/DEC system: (a) work diagram and (b) the psychometric process.

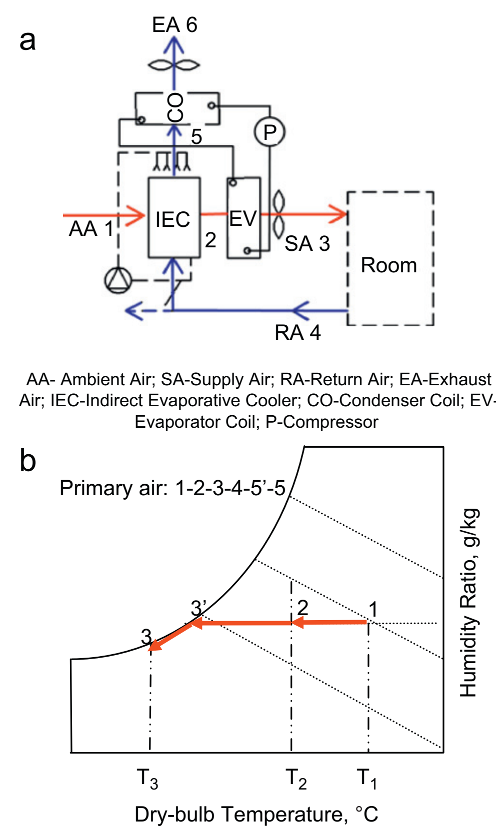


Fig. 15. Two-stage IEC/direct-expansion system: (a)work diagram and (b) the psychrometric process.

illustration of the air treatment process is shown in Fig. 15(b). The (product) air was cooled in the IEC unit prior to entering into the downstream cooling coil (served with either chilled water or refrigerant), which resulted in a measurable saving in electricity consumption of the compressor. In such a system illustrated in Ref. [53], the secondary air for use in the IEC was the room return air which had the inlet temperature of 18–20 °C and achieved the state of 21–24 °C *db* at 80–90% rh, at the outlet of the IEC. This part of air was further utilized to cool the condenser of the mechanical compression refrigeration based system, thus further improving the performance of the system due to the reduced cooling air temperature within the air condenser. The product air, after leaving off the IEC, was brought into the cooling coil (water or refrigerant) for further cooling and at its outlet, the temperature of the air fell to 15 °C or below which is lower enough to cool the building space as required.

(3) **IEC/DEC/cooling coil (chilled water or refrigerant) combined system**
When extra low temperature air is needed at a special occasion such as freezing rooms, combination of the three units, i.e., IEC, DEC and cooling coil, could be brought into use [54]. Fig. 16(a) shows a general layout of such a system and Fig. 16(b) is the psychometric illustration of the dedicated air treatment process occurring in the system operation. The primary air was cooled by three stage operation at IEC, DEC and cooling coil (CC), thus reaching a required low temperature and being delivered to the room space; whereas the room return air was utilized as the coolant (secondary air) at the IEC to cool the primary air with the aid of water

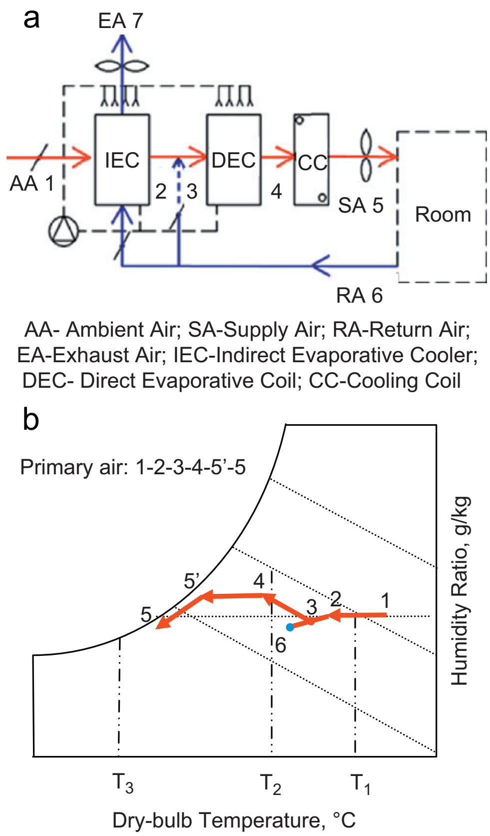


Fig. 16. Three-stage IEC/DEC/cooling coil system: (a) work diagram and (b) the psychrometric process.

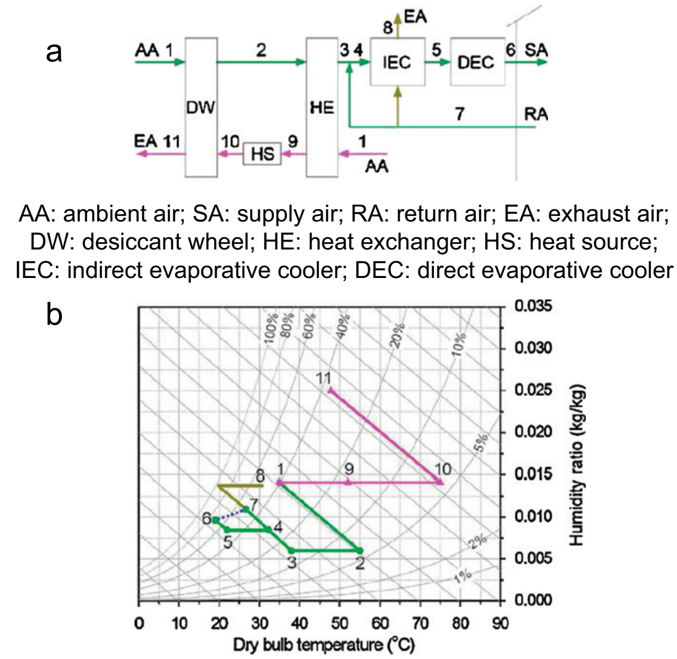


Fig. 17. Desiccant/IEC/DEC system (DINC cycle): (a)work diagram and (b) the psychrometric process [57].

evaporation. This process, compared to the above two operational modes, had higher level of complexity in configuration but as a trade-off, could obtain increased cooling effectiveness and capacities. Refs. [55,56] reported the similar systems using combined IEC/DEC/cooling coils.

(4) **Desiccant/IEC/DEC System**
With the continuous technical progress in air dehumidification treatment, separate control of the humidity and temperature of the air has gained growing popularity in recent years. The approach is to use a desiccant cycle to remove the moistures and certain amount of latent heat generated from the moisture condensation, and use the IEC and (or) DEC units to treat the sensible cooling load and remaining latent heat from the moisture condensation. A desiccant is a solid- or liquid-state water affinity chemical. Traditional solid desiccants (also called 'adsorbents') include sillion gel, acivated aluminium, lithium chloride (LiCl) salt, zeolites, molecule sieves, titanium silicide and polymer etc, which all have porous structure enabling binding of moistures in the voids; whilst the commonly used liquid desiccants (also called absorbents) are lithium chloride (LiCl), lithium bromide (LiBr), calcium chloride ($CaCl_2$) and potassium formate (KCOOH) solutions.
To operating a solid desiccant cycle, the fixed bed and rotary wheel are two available structures. Fig. 17(a) shows the general layout of such a combined desiccant/IEC/DEC system and Fig. 17(b) presents a psychometric illustration of the air treatment process occurred during the system operation [57]. A rotary wheel was utilized in this system; part of the wheel block absorbed the moistures from the passing air and led to dry-out of the air and change of state from 1 to 2; while the other part of wheel block was regenerated using a higher temperature air flow, leading to vaporization of the reserved moisture within the wheel voids and subsequent cooling using the colder air. The primary air of state 2 was then passed across a heat exchanger, transferring heat to the regeneration air which is usually ambient air and changing state from 2 to 3. Further, the air experienced a dry cooling at the IEC and constant-enthalpy cooling at the DEC, leading to changes of the state from 3, 4, 5 and 6, and finally was delivered to room space for purpose of cooling. In parallel, the regeneration air, i.e., ambient air, experienced a temperature rise at the heat exchanger (HE) thus changing state from 1 to 9, further temperature rise at the heat source (HS) leading to the state change from 9 to 10, and the constant-enthalpy cooling process at the rotary wheel, causing the change of state from 10 to 11. This method, having potential to eliminate use of the mechanical vapour compression system and therefore, is considered an energy efficient measure for air conditioning. During this process, the heat source (HS) could be either solar energy or a low grade waste heat which could further reduce use of fossil fuel and improve energy efficiency of the system. Ref. [58] concluded that the Coefficient of Performance (COP) of such a system was as high as 1.6. Similar applications of such a system were reported in Refs. [58,59].

4. Researches and achievements related to the IEC

Many research works on the IEC have been reported and the focuses were given to analyse the heat and mass transfer process, evaluate the performance of various types of flow patterns under various operational conditions, optimise the configurations and geometries of heat exchanger and water/air distribution, select the suitable materials for heat exchanger making, suggest the favourite operational conditions and evaluate the energy saving and carbon reduction potentials. A summary of the research works and achievement is given below.

4.1. Material study

The properties of the heat/mass exchanging medium (wall material) are important as these have direct impact to the

performance, particularly the cooling efficiency (effectiveness), of the Indirect Evaporative Cooling (IEC) systems. Unlike the DEC, the heat and mass transfer taking place at the wet channels of the IEC is simultaneously coupled with the sensible heat exchange between the air and 'wall' occurred at the dry channels of the IEC. In the wet channels of an IEC, a material layer that is able to distribute and hold water is always needed to enable the evaporation of the water and thus induce the sensible heat exchange on the adjacent dry channels. This increases the contact area between the wall and the wet channel working air and thus helps the heat transfer between the dry and wet channel air.

Plastic plate is first kind of this material used in making IEC heat exchangers [60]. It has advantages of light weight and corrosion-less. However, the poor thermal conductivity and low strength tension limited its wide application in IEC making. In recent years, fibre materials, including cellulose, conconut, palash, palm stem, Jute tossa, Luffa gourd and Aspenwood excelsior, Kraft and NSSC types, [61–64] have been brought into use. In overall, the fibres have good water permeability that allows water to spread across the wet surface and create good evaporation and heat transfer effect. On one side of the fibre sheet, either a water proof coating or an aluminum foil (sheet) is laid to keep the dryness of the air on the dry channels of the IEC heat exchanger.

Zhao et al. [31] carried out a comparative study into several IEC available materials, including metals, fibers, ceramics, zeolite and carbon. It is suggested that the thermal properties of the materials, i.e., thermal conductivity and water retaining capacity (porosity), have little impact to the IEC's heat/mass transfer, and therefore, these two parameters play low keys in terms of material selection. Instead, shape formation/holding ability, durability, compatibility with water-proof coating, contamination risk as well as cost, are more important concerns in this regard. The wick (sintered, meshes, groves and whiskers) attained metals (cooper or aluminum) are the most appropriate structure/material over the others.

In overall, a good heat/mass transfer material for the IEC should be heat and moisture conveying, allowing effective cooling of the product air using evaporation aided heat transfer between the product and working air. It should also be less resistant to the passing air to minimize the pressure drop within the IEC and thus reduce associated fan power. The material should be cheap and suitable for shaping into various geometries. Further, it should be ease of cleaning and replacement and able to avoid bacterial growth on the wet surface.

4.2. Mathematical theory and computer simulation

This part of research was aimed at finding right mathematical methods (equations) and converting those into dedicated computer models to simulate the heat and mass transfer process occurring in the heat exchanger and whole IEC system. This resulted in solutions of the operational characteristics of the water evaporation assisted heat exchange, optimisation of the geometrical shape and sizes of the exchanger and whole system, recommendation of the suitable operational conditions such as climatic regions, as well as prediction of the energy saving and carbon reduction figures.

In overall, theoretical and computer modelling works could be classified into three categories: analytical resolution, one- and two- dimensional numerical simulation. The analytical modelling made use of traditional thermo-fluid theory to develop general solutions to the most important operational parameters and establish relation between these and other associated parameters. A number of selected analytical works are given below:

Analytical work—case 1: Maclaine-cross and Banks [17] developed an analytical model dedicated to the indirect evaporative cooling process which was compared with the published data relating to the IEC heat exchangers. The predicted efficiency of the model was found to be 20% higher than the published experimental data, and reasons for this difference were attributed to a few assumptions made: (1) humidity ratio of the air, in equilibrium with water surface, is linear to the water surface temperature; (2) water film on the wet surface was steady and continuously fed to match the evaporation of the water; (3) wet surface was completely saturated; and (4) Lewis relation was fully applicable to this operation.

Analytical work—case 2: Stoitchkov and Dimitrov [20] proposed a method of calculating the cooling effectiveness of the cross-flow flat-plate heat exchanger by analysing the characteristics of the pre-set flowing water film, determining the mean water temperature on the wet surface and developing an equation to calculate the ratio of the total to sensible heat, by taking into account the barometric pressure. The discrepancy between the modelling results and the published experimental data was found to be in the range 2–4%.

Analytical work—case 3: Alonso et al. [19] developed a simplified heat and mass transfer model enabling analyses of the thermal performance of the cross-flow flat-plate heat exchanger based IEC including prediction of the system energy consumption, design of the system configuration and optimisation of the geometrical sizes of the system setting. This model introduced an equivalent water temperature that was used in calculation of the heat transfer between the primary and secondary air. A discrepancy of the average 0.54 °C in predicted and tested supply air temperature was found in existence [14,18].

Analytical work—case 4: Erens and Dreyer [18] made through comparison among three available analytical methods, and suggested that (1) the Poppe method [65,69] is appropriate for use in accurate prediction which gave the assumption that the secondary air is supersaturated with water vapour; (2) Merkel method [66] is the simplified version of the Poppe method which assumed that (a) a constant Lewis factor is in existence, (b) sprayed water has constant temperature and (c) the secondary air is saturated (rather than supersaturated) with water vapour, thus leading to reduced accuracy in prediction against the measurement; (3) a more simplified method developed by Erens and Dreyer [18] is suitable for evaluation of smaller sized systems and development of initial design scheme; this method has larger discrepancy owing to the assumption that the recalculated spray water has constant temperature throughout the cooling surface and over the whole duration of the process.

Many analytical works could be found in recent journal publications [75–84]. Table 5 provides a summary of the most representative works in this regard.

To explore the details of the heat and mass transfer process occurred in the IEC heat exchangers including temperature, humidity, velocity, pressure of the airstreams within the dry and wet channels, water temperature/evaporation-rate etc, and thus enhance the accuracy of the model prediction to the actual operation of the exchangers, numerous one-dimensional numerical models were developed [17–20,28,48,58,66–74] on basis of the above mentioned analytical works. During the model set-up processes, a few common assumptions were made: (1) heat is transferred vertically across the separating plate, no heat flow occurs along the air flow direction; (2) air flow across the channel is uniform; (3) water deposited into the wet surface of the wall travels vertically to the passing air; (4) the wet surface of the wall is entirely saturated with water, and (5) air is treated as an incompressible gas. This allowed establishment of a group of differential equations illustrating the heat and mass transfer among the primary, secondary air and the spreading water across the wet surface of the exchanging sheets, conversion of the equations into the computerised numerical programmes, and running up the programmes to give out solutions to the questions. There were several simplified models that, owing to further assumptions made including (1) the water film is in sta state; (2) the circulating water

Table 5
Summary of the computer modelling and mathematical analyses.

Model type	No	Mathematical method	Case selected	Operating condition	Experiment Validation	Accuracy	Features and recommendation
Analytical model	1 [20]	Finite difference method	Cross-flow plate IEC	$t_{p,db,in}$=24–36 °C, $t_{p,wb,in}$=17.7–28.3 °C, $t_{s,db,in}$=22–28 °C, $t_{s,wb,in}$=16–21 °C, u_p=3.3 m/s, m_s/m_p=0.5	Yes	< 4% in cooling effectiveness	Based on [17] but with some improvements on assumptions and give more accurate predictions: flowing water film; determination of mean water temperature; considering barometric pressure in the ratio of the total to sensible heat
	2 [21]	Analytical method	Parallel and counter-flow plate IEC	$t_{p,in}$=21–50 °C, $t_{s,in}$=21–35 °C, $w_{s,in}$=9.41–21.71 g/kg	No (but verified with other numerical models)	Good agreement: Average 0.17% error in supply air temp	Sophisticated model High accuracy Considering varieties of Lewis factor, surface wetting condition, effects of the evaporation and flow rates, temperature and enthalpy of the sprayed water Four different flow configurations were discussed using the model
	3 [76]	ε-NTU method	Counter-flow regenerative cooler	$t_{p,db.in}$=34.2 °C, $t_{p,wb.in}$=15 °C, m_s/m_p=0.95	Yes	7.4% in supply air temp	Simple and precise modified model Following the same steps used in the solution of the sensible heat exchanger Applicable to any type of indirect evaporative cooler
	4 [19]	Finite difference method	Cross-flow plate IEC	$t_{p,db,in}$=35–45 °C, $t_{p,wb,in}$=19.5–23.3 °C, $t_{s,db,in}$=23.5–27.2 °C, $t_{s,wb,in}$=16.8–18.6 °C, V_p=0.022 m^3/s, m_s/m_p=0.5	Yes	Average 0.54 °C error in supply air temp	A simplified model suitable for performance prediction, IEC configuration design and geometrical optimisation. Introduction of an equivalent water temperature The model is applicable to other geometries and operation conditions
One-dimensional numerical model	5 [70]	Finite difference method	Counter flow and parallel flow regenerative cooler	$t_{p,db,in}$=30 °C, $t_{p,wb,in}$=18.8 °C, $m_{p,in}$=0.0014 kg/s, $m_{s,in}$=0.00098 kg/s	Yes	7.4% in supply air temp	A method of providing supply air at temperatures lower than the ambient wet bulb temperature A simple numerical model
	6 [97]	Finite differential method, Newton iterative method	M-cycle counter-flow plate IEC	$t_{p,db,in}$=25–45 °C, $w_{p,in}$=6.9–26.4 g/kg, u_p=1.5–6 m/s, m_s/m_p=0.33	Yes	5% in supply air temp; 10% in cooling effectiveness	Covering various inlet air conditions (dry moderate and humid climate) Simulated the influence of major operating parameters (velocity, system dimension and the ratio of working air to intake air) on the thermal performance Compared with the numerical results from [31]
	7 [28]	Finite difference method and Newton iterative method	M-cycle cross-flow plate IEC M-cycle counter-flow plate IEC	$t_{p,db,in}$ =25–40 °C, RH_P=50%, V_p=130 m^3/h $t_{p,db,in}$=25–45 °C, $w_{p,in}$=6.9–26.4 g/kg, u_p=2.4 m/s, m_s/m_p=0.33	Yes Yes	0.2–0.4% in cooling effectiveness < 3.4% in supply air temp	Original comparative study between M-cycle cross-flow and counter-flow IEC in terms of cooling effectiveness and pressure drop under same geometrical size and operation conditions. Parametric study into the effects of on performance of M-cycle cross and counter-flow IEC
	8 [47]	Finite difference method	Cross-flow plate IEC	$t_{p,db,in}$=25–45 °C, $t_{s,db,in}$=25.0 °C, $t_{s,wb,in}$=11.4–23.8 °C, u_p=0.5–4.5 m/s, m_s/m_p=0.5–2	No	N/A	The effects of various parameters, i.e., primary and secondary air velocities, channel width, inlet relative humidity and wet ability of plate on the cooling effectiveness were examined
Two-dimensional numerical model	9 [80]	Finite difference, ε-NTU and iterative numerical method	Cross-flow plate IEC	$t_{p,db,in}$=30–45 °C, $t_{p,wb,in}$=15,20,25 °C, m_pc_p/m_sc_s=0.5–10	No (but verified with other published models)	Good	Influence of longitudinal heat conduction in cross-flow plate IEC The performance deterioration due to longitudinal heat conduction effects was determined for various design and operating conditions

temperature is constant throughout the exchanging sheet surface; and (3) Lewis number is a constant, led to reduced accuracy in prediction of the system performance. However, several dedicated models [19,20,63,64] that, owing to consideration of the actual restriction of the heat exchanger operation, e.g., the variation of circulating water temperature, difference between water circulation and evaporation rates, as well as incomplete wetting condition on the wet surface [71], were found to be able to achieve higher level of

accuracy in terms of performance prediction. A number of one-dimensional numerical cases are given below:

One dimensional numerical modelling work—case 1: To narrow up the gap between the measurement and modelling results, Kettleborough and Hsieh [67], on basis of the work made by Maclaine-cross and Banks [17], developed a one-dimensional numerical model for the counter-flow flat-plate heat exchanger based IEC unit. This model took into account the factors of incomplete wetting and variation of the sprayed water temperature across the heat exchanging plate surface, and thus lowered the difference between the modelling and experimental efficiency down to 14%.

One-dimensional numerical modelling work—case 2: Guo and Zhao [47] conducted dedicated analyses into the thermal performance of a cross-flow indirect evaporative cooler, with particular focus on the effects of various parameters, i.e., primary and secondary air velocities, channel width, inlet relative humidity and wet ability of plate to the cooling effectiveness of the system. This therefore contributed to obtain the highest possible heat and mass transfer rate and reduced pressure drop across the exchanger setting. It is found that a smaller channel width, a lower secondary air inlet relative humidity, a higher wet ability of the plate and a higher ratio of the secondary-to-primary air yielded a higher cooling effectiveness of the IEC.

Many one-dimensional numerical works could be found in recent journal publications. Again, Table 5 provides a summary of the most representative works in this regard.

Two dimensional numerical simulation works were also developed aiming at studying the distribution of air flow, temperature and humidity along both vertical and horizontal directions within an IEC heat exchanger. A number of two dimensional numerical simulation works are introduced below:

Two dimensional numerical simulation work—case 1: Ren and Yang [21] developed an enhanced analytical model able to simulate the coupled heat and mass transfer processes in parallel and counter-current IEC heat exchanger under various operating conditions. In contrast with the above one-dimensional models, this model solved the coupled heat and mass transfer equations by taking into consideration of the varieties of Lewis factor, surface wetting condition, effects of the evaporation and flow rates, temperature and enthalpy of the sprayed water. Compared to the solutions derived from the one-dimensional models, much smaller discrepancy (0.17% to the supply air temperature, 0.64% to the secondary outlet air temperature, and 0.24% to the secondary outlet air humidity ratio) were achieved by using the enhanced model. The study indicated that the counter current flows within the flat-plate heat exchanger, i.e., the primary air travelling in the counter-current direction to the secondary air and water film, could achieve the best performing operation in a fixed heat exchanger, and no heat conduction was found in the longitudinal (air flow) direction in the exchanger wall.

Two dimensional numerical simulation work—case 2: Hettiarachchi et al. [80] investigated the influence of two dimensional longitudinal heat transfer in the plate wall within a compact flat-plate cross-flow heat exchanger by using the NTU method. The convective heat transfer within both the dry and wet channels and the mass transfer within the wet channels were considered by using a group of governing equations, while solving of the equations were made using the iterative numerical method. This study indicated that the deterioration in cooling effectiveness of the IEC by the longitudinal heat conduction was about 10% or higher under typical operating conditions while less than 5% was found in some conservative conditions.

There are numerous two-dimensional numerical works reported in the recent journal publications. Again, Table 5 provides a summary of the most representative works in this regard.

4.3. Experimental work and model validation

This part of works was aimed at testing the operational characteristics of the IEC exchangers/systems under the controlled laboratory and real building/climatic conditions and further, to verify or modify the effectiveness of the computer model on predicting the performance of the system.

In terms of laboratory based works, tests were undertaken aiming to understand the performance of the IEC exchangers/systems, including cooling effectiveness, cooling capacity (output), energy efficiency (COP and EER), and temperature reduction potential, etc. The purpose of the tests were (1) verifying/modifying the established computer models; (2) understanding the operational performance of the IEC exchanger/system under the controlled laboratory conditions; (3) establishing the relationship between various operational parameters relating to the IEC exchanger/system; (4) suggesting the approach to modify or optimise the geometrical configuration of the IEC exchanger/system; and (5) recommending the favourite operational conditions of the IEC exchanger/system. A number of lab-based testing cases are introduced below:

Lab based work—case 1: Qiu [22] carried out a lab-based testing to a small scale IEC prototype. The testing results indicated that real performance of the IEC unit was much lower than the values given by the product catalogues. Reasons for reduced performance lied in the poor water distribution of the unit, which gave only 1/2 to 2/3 of flat-plate surface when in operation. To resolve the problem, he installed a top water spraying device and had it integrated with a solar-powered PV panel which supposed to provide electrical energy needed for fans and pump operation. The modified unit was retested and the results showed that the cooling capacity and COP of the new unit were 3 times high than that of the old one. The temperature drop of the primary air between the inlet and outlet of the unit was in the range 3–8 °C.

Lab based work—case 2: Tulsidasani et al. [85] studied the relation between Coefficient of Performance (COP) of a tube type IEC and the primary and secondary air velocities using both modelling and testing methods. A good agreement was achieved between the theoretical predicted and experimentally tested COPs for an IEC at Indore (India) summer operation. It was found that the maximum COP of the IEC unit was 22 at the primary air velocity of 3.5 m/s and the secondary air velocity of 3 m/s, leading to 10.4 °C of the primary air temperature drop.

Lab based work—case 3: Jain [87] developed a two-stage evaporative cooler comprising of a flat-plate heat exchanger and two evaporative cooling chambers, in order to enhance the effectiveness of evaporative cooling under high humidity ambient condition and low temperature indoor air requirement. The performance of the cooler was evaluated in terms of temperature drop, efficiency of the IEC heat exchanger and cooling effectiveness of the two-stage evaporative cooler over the single-stage one. The two stage cooler, able to create 8 °C to 16 °C of air temperature drop, could provide the cold air close to the wet bulb temperature of the ambient air and with 90% of relative humidity. It had a cooling effectiveness of 1.1–1.2 while the single evaporative cooler had only wet bulb effectiveness of 0.85–0.9.

Lab based work—case 4: Velasco Gómez et al. [88] carried out an experiment study into a polycarbonate-made indirect evaporative cooling unit under two operational modes. The first mode used the exhaust air leaving off the climate chamber as the secondary air of the heat exchanger and the outdoor air as the primary air; while the second, when remaining other conditions same, added up a water spraying measure into the exhaust air flow. The experimental results indicated that the IEC prototype could obtained higher cooling capacity and also increased cooling effectiveness when spraying water against the exhaust air.

Further, higher outdoor air temperature or air flow rate helped obtain enhanced cooling performance of the system.

Lab based work—case 5: Jiang et al. [45] developed and tested a novel indirect evaporative chiller for use in providing cooling water for the building HVAC systems. The test results indicated that the outlet water temperature could be reduced to around 14–20 °C, lower than the inlet air wet bulb temperature and higher than its relevant dew point temperature. The chiller's COP was in the range 0.4–0.8.

Lab based work—case 6: Costelloe and Finn [89] developed a method of analysing the availability of evaporative cooling water for Dublin and Milan by incorporating the recent experimental findings and meteorological test reference weather year data. Further, they [90] experimentally studied the impacts of the key operational variables (e.g., ambient wet bulb temperature, cooling tower air-flow rate, primary and secondary water-flow rate) to the cooling effectiveness of a testing system comprising an open cooling tower and plate heat exchanger. They found that the cooling tower air-flow rate and secondary water-flow rate have a strong impact to the cooling effectiveness of the system; this result helped obtain an energy efficient control strategy towards the fan and pump in the system which would enable adaption to various cooling loads and climatic conditions encountered in practical operation.

Many lab based works could be found in recent journal publications. Table 6 provided a summary of the most representative works in this regard.

In terms of the building based works, tests were undertaken aiming to understand the real performance of the IEC exchanger/system and the whole building at a real climatic condition. The purpose of the tests were (1) verifying/modifying the established computer models; (2) understanding the actual operational performance of the IEC exchanger/systems under the real building and climatic conditions; (3) energy saving and carbon emission reduction potential relating to the IEC implementation into buildings; (4) suggesting the approach to modify or optimise the configuration of the IEC exchanger/system; and (5) recommending the favourite climatic conditions adaptable to the IEC exchanger/system operation. A number of building-based testing cases are introduced below:

Building based work—case 1: Tulsidasani et al. [85] studied the thermal performance of a non-air-conditioned building equipped with an IEC system. For three different climatic conditions at India (dry/hot, humid/hot, humid/warm), effects of various IEC parameters to thermal comfort of the building space was investigated. The results indicated that the IEC system is effective in improving the thermal comfort of the buildings in dry/hot climatic condition.

Building based work—case 2: Performance of the combined IEC/DEC systems were experimentally studied by Scofield [86], Al-Marafie et al. [3], Heidarinejad G [23] and Jain [87]. In Ref. [86], the IEC/DEC system passed the primary air into a IEC flat-plate heat exchanger for dry cooling and then to a conventional cooling tower for adiabatic cooling. The testing results indicated that such a system could achieve 30% of fossil fuel energy saving over the same sized conventional mechanical compression refrigeration based air conditioning system.

Building based work—case 3: El-Dessouky et al. [3] introduced a combined IEC/DEC unit installed on a building in Kuwait where the ambient dry bulb temperature in summer is often above 45 °C. The thickness of the wet packing (for DEC) and water flow rate across the DEC were found to impose significant impact to the performance of the system. The test results indicated that the cooling effectiveness of the IEC/DEC system was in the range 90–105% while the IEC part contributed only 20–40% in terms of its cooling effect. These test data were used to correlate the Nusselt number for the airstreams outside the IEC heat exchanger, which was found to be in the range 150–450, giving the corresponding heat transfer coefficient of 0.1–0.4 kW/m^2 k. These results also showed good agreement to the literature data for the same condition and so provided references for design of the IEC units.

Building based work—case 4: Heidarinejad et al. [23] reported an experimental investigation of a two-stage IEC/DEC system operated in Iran's climatic condition, with focusing on the effect of the outdoor air conditions on cooling effectiveness of the system. The IEC/DEC system comprised of a plastic flat-plate heat exchanger and a 15 cm thick of cellulose pad, with the unit sizes of 500 × 500 × 400 mm, respectively and the channel spacing of 7 mm. During the testing, the primary and secondary air flow rates were adjusted to 1700 and 850 m^3/h, respectively. The test results indicated that under different inlet air parameters, (inlet dry/wet-bulb temperature: 27–49 °C/15–33 °C), the wet bulb effectiveness of the system was in the range 108–111%, while the single IEC system had a cooling effectiveness of 55–61%. The average water consumption of the system was 55% higher than the single direct evaporative cooling system, and the energy efficiency (or COP) of the system was in a range 8–9. Compared to the typical mechanical vapour compression refrigeration based systems which have a COP of around 3, the two-stage IEC/DEC system could obtain more than 60% saving in terms of the fossil fuel energy consumption.

Many building based works could be found in recent journal application. Table 6 provides a summary of the most representative works in this regard.

In summary, the individual IEC operation could achieve the wet bulb effectiveness as high as 0.4–0.9; its COP varied from 5 to 15 depending upon size and complexity of the system; while air temperature drop was between 5 and 10 °C. The IEC system had very positive cooling effect to the non air-conditioned buildings at the hot regions like India. The combined IEC/DEC operation was found to be able to achieve enhanced cooling effectiveness as high as 90–120%, while the contribution from IEC part is about 20–60%. The COP of the combined system was in the range 8–22, which is 3 times higher than the typical mechanical vapour compression refrigeration based air conditioning systems. This type of system had potential to lower air temperature by 8–16 °C and obtained 90% of relative humidity of at the outlet of the unit, allowing the outlet air to approach the inlet air's wet-bulb temperature. The system could achieve 30–60% fossil fuel energy saving over the same sized conventional mechanical vapour compression refrigeration system. In terms of water consumption, the combined system is 50–60% higher than that in a direct evaporative cooling system.

4.4. Effect of the water distribution

The predicted heat and mass transfer of the IEC could only be achieved on the condition of obtaining complete wetting of the wet channels surfaces. Poor water distribution on the surfaces would reduce the heat/mass transfer rate between the primary air and the water film, and between the water film and secondary air, which would eventually undermine the effectiveness of the indirect evaporative cooler.

The most commonly used water spraying method in indirect evaporative coolers is by sparking nozzles, as shown schematically in Fig. 18 [91]. The nozzle sprayers are positioned above the cross-flow heat exchanger, sprinkling the atomized water drizzles over the upcoming secondary airstreams. The water, when sprayed into the wet channels, wets the surface of the channels and enables the heat/moisture exchange between the water and the secondary air, thus causing evaporation of large proportion of water. Meanwhile, the remaining water drops into the bottom

Table 6
Summary of the experimental work and computer modelling validation.

Experimental type	No	Testing method	Case selected	Operating condition:	Comparison to model	Accuracy	Features and recommendation
Lab testing	1 [85]	Power consumption, static pressure, air dry-bulb temperature, RH, air velocity	Tube type IEC	$t_{p,db,in}$=41–45 °C, u_p=3–8 m/s, u_s=3–4 m/s	Yes	< 1.28% in COP	Study of relation between COP and the primary and secondary air velocities
	2 [29]	Airflow rate, Air dry-bulb, dew-point temperatures, pressure, power consumption, water flow rate, fan speed	M-cycle cross flow plate IEC	$t_{p,db,in}$=26.7–43.8 °C, $t_{p,wb,in}$=18.1–23.9 °C, u_p=0.53–1.38 m^3/s	No	N/A	The test plan was based on ASHRAE test standards for evaporative coolers The test conditions cover various cooling design conditions computer modelling and field testing should be undertaken
	3 [24]	Air dry-bulb and wet-bulb temperature, air velocity	M-cycle counter-flow plate IEC	$t_{p,db,in}$=24–45 °C, $w_{p,in}$=6.9–26.4 g/kg, u_p=2.4 m/s	Yes	5% in supply air temp; 10% in effectiveness	Static and dynamic testing under different inlet air temperature and moisture content Compared with previous studies
	4 [22,28,95]	Air dry-bulb temperature, humidity ratio, RH, air velocity	M-cycle cross-flow plate IEC	$t_{p,db,in}$=25–40 °C, $RH_{P,in}$=50%, V_p=0.036 m^3/s	Yes	0.2–0.4% in cooling effectiveness	Comparative study between M-cycle cross and counter-flow IEC Parametric study
			M-cycle counter-flow plate IEC	$t_{p,db,in}$=25–45 °C, $w_{p,in}$=6.9–26.4 g/kg, u_P=2.4 m/s, m_s/m_p=0.33	Yes	< 3.4% in supply air temp	Optimisation of geometry and operating conditions of the IEC
	5 [26]	Air dry-bulb temperature, RH, air velocity, fan power and water consumption	Cross-flow plate IEC	$t_{p,db,in}$=39–43 °C, $RH_{p,in}$=37–46%, V_p=0.065–0.843 m^3/s, V_s=0.833 m^3/s	No	N/A	Different shapes and cooling media in direct stage to be test, respectively with the IEC stage.
	6 [111]	Air temperature, power and water consumption, air velocity	IEC (M-cycle cross-flow)/DX	$t_{p,db,in}$ =28.4–32 °C, $RH_{p,in}$=38–87%, V_p=1.58–1.69 m^3/s, V_s=0.67–0.77 m^3/s, m_s/m_p=0.42–0.62	No	N/A	Coolerado RTU was tested at the NREL HVAC laboratory The inlet air is the combination of return and outdoor air
	7 [56]	Air dry-bulb temperature, RH, air velocity	Desiccant/ IEC (cross-flow plate type)	$t_{p,db,in}$=28.3 °C, $RH_{p,in}$=60%, V_p=0.35 m^3/s, V_s=0.35 m^3/s	No	N/A	Desiccant evaporative cooling and indirect evaporative cooling were used to increase the energy performance and reduce energy consumption
	8 [23]	Air dry-bulb temperature, RH, water flow rate, air velocity	IEC/DEC	$t_{p,db,in}$ =27–49 °C, $T_{p,wb,in}$=15–33 °C, V_p=1700, V_s =0.236 m^3/s	No	N/A	covering multi-climate conditions in Iran Comfort and power saving were studied with excess water consumption Theoretical/numerical analysis should be done
Building based testing	9 [45]	Output water temperature, Power consumption, air dry-bulb and wet-bulb temperature, air flow rate	indirect evaporative chiller	$t_{p,db,in}$ =19.6–38 °C, $t_{p,wb,in}$=15.4–23.3 °C, m_{in}=1 kg/s, m_{fresh}=0.6 kg/s	No	N/A	can generate cooling water at a temperature below wet-bulb of ambient air (14–20 °C) simulation and field testing studies should be compared Indoor comfort conditions were satisfied
	10 [98]	Air dry-bulb temperature, humidity, power consumption and air flow rate	M-cycle counter-flow plate IEC	Commercial application: $t_{p,db,in}$=22.5–40.3 °C, RH_p=10–55%, Residential application: $T_{p,db,in}$=27.5–40.4 °C, RH_p=12.8–32.2%	No	N/A	Results obtained from testing a prototype cooler installed in both a commercial and residential application in a wide range of ambient conditions.
	11[53]	Air dry-bulb temperature, RH, power and water consumption	IEC (M-cycle cross-flow plate type)/DX	$t_{p,db,in}$=21–43 °C, $t_{p,wb,in}$=11–24 °C	No	N/A	50% energy saving EER: 19–25 significantly beyond other products on the market. lab and field testing results

sump and is then pumped up to the top nozzle sprayers for reuse. In this method, the surface of the wet channels and the upcoming secondary airstream are cooled, enabling them to absorb the heat coming across the adjacent dry channel (primary) airstreams, thus leading to the temperature fall of the primary air. This method, having been in use for many years, was found a number of problems [92,93]: (1) uniform water distribution is hard to achieve when the velocity/pressure of secondary air are relatively high and channel spacing is relatively large; (2) even distribution of water flow by using the nozzle sprayers is difficult to obtain; (3) the atomization capacity of the nozzle sprayers is often oversized for conservative consideration, leading to larger than expected water circulation rate and pump power; (4) the selected pump could not match exactly the demand for water evaporation in the circulation, causing either larger or smaller water delivery than needed; and (5) the hydrophilic performance of the wet channel surface is unsatisfactory that prevent uniform spreading of the water across its surface.

Numerous researches and practical investigations were carried out to tackle the above addressed problems and the studies were focused on [92]: (1) water distributor configuration; (2) water spray density or optimal water spray volume, which is determined by the structure, diameter and spacing of the nozzle sprayers; (3) water distribution mode; (4) water retention ability of the wet surface and (5) spacing of the wet channels.

Wang studied the effect of the wettability (surface wettability factor is the parameter used to estimate the effect of incomplete wetting) of aluminium plates to the cooling performance of the indirect evaporative systems [94]. A dynamic contact analyser was applied to quantitatively measure the advancing and receding contact angles and the water-retention capacity of different aluminium surfaces. Most wicked surfaces were found to have at least zero receding contact angles and some of those had zero advancing contact angles, which are unfavourite to creating even water distribution, and also to generating sufficient water retention and the system's cooling effectiveness. Coating a harsh fibre on the surface was found to be an effective way to increase the water retention and thus cooling effectiveness of the IEC heat exchanger.

Zhou [93] carried out a study into the optimisation design of water distributor to improve the water distribution uniformity of the IEC. This research outlined several available water distributors and water distribution modes applicable to the IEC. The method of calculating theoretical water spray volume of the IEC was analyzed, and the approaches for improving uniformity of water distribution were suggested. There are three commonly used water distribution modes, namely, upper, middle and bottom spray layout, which are schematically shown in Fig. 19. It is suggested that (1) the upper water spray layout can be applied to most IEC configurations, and can create a counter water-flow streams against the secondary air. (2) the middle water spray layout is difficult to install but may create effective water distribution at larger exchanger block by spreading the water either counter or current to the secondary airstreams; (3) bottom water spray layout may be used in the sites where the installation space is limited; this would create the water streams current to the secondary airstreams. The further approaches of improving water distribution include: (1) increasing channel spacing up to 10 mm; (2) reducing the secondary air velocity; (3) enhancing the water retention capacity of the wet surfaces through rolling dot matrix twill or grooves lines; (4) installing the water distributors

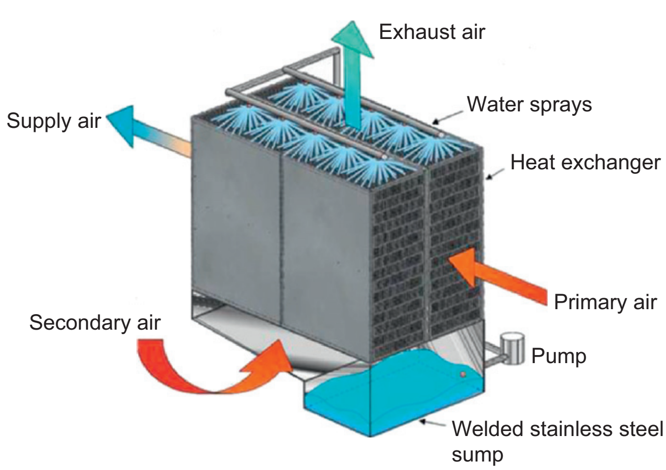


Fig. 18. Schematic of water sprays in indirect evaporative coolers [91].

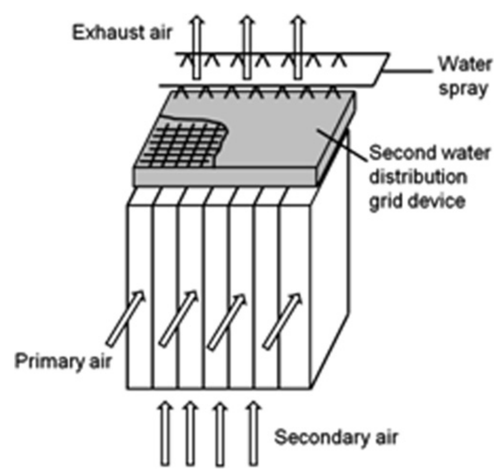


Fig. 20. The second water distribution grid device of IEC [49].

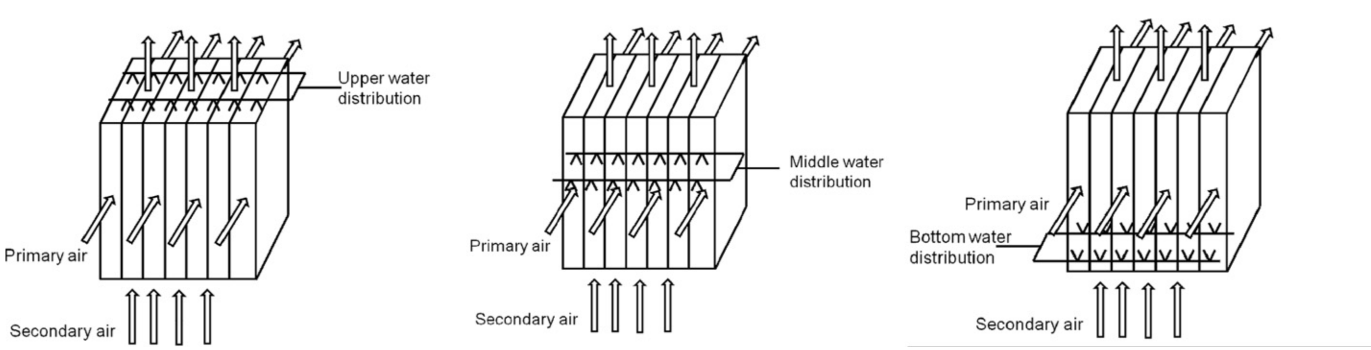


Fig. 19. Three water distribution modes used in IEC [49].

to appropriate position to create the right water streams; and (5) adding up a second water distribution grid beneath the first water sprays, as shown in Fig. 20.

In recent years, a new type of water distribution method was applied to the IEC unit [95] and this used the regularly perforated, small sized tubes that were laid on the slots of the wet channels to discharge the water streams to the wet surfaces of the channels. The water streams, when flowing downward along the channel walls, spread across the walls along the horizontal direction and owing to the permeability effect of the wet surfaces and small flow rate of the water streams, the water quickly spread along the horizontal direction and thus formed uniform distribution of the water across the walls. In this case, the flow rate of the water was 2–3 times of the water evaporation rate.

4.5. M-cycle IEC systems and associated performance measures

A new M-cycle IEC system [34] was developed to enable obtaining enhanced cooling effectiveness, reduced supply air temperature and increased per unit volume cooling capacity compared to conventional IEC systems. Its system configurations, associated theories and computer models, experimental testing and performance evaluation measures were broadly studied in recent years [11,29–32,96,97].

Pacific Gas and Electric Company carried out a lab-based testing for the Coolerado Cross-Flow M-Cycle IEC unit [29]. Effect of the inlet air dry/wet bulb temperatures, outlet back-pressure, fan speed, airflow rate to performance of the unit including cooling effectiveness, cooling capacity, power consumption, cooling capacity, energy efficiency and water evaporation rate were broadly investigated using the experimental method. The testing results indicated that the wet-bulb effectiveness of unit varied from 81% to 91% over the full range of testing conditions, which is 15–30% higher than that of the normal IEC systems. Under all sets of testing conditions, the unit could provide a supply air of 18.9–25.6 °C in dry-bulb and 30–80% in relative humidity. The average energy efficiency (COP) of unit was over 8.8, leading to 40–80% reduction in fossil fuel energy consumption relative to the normal IEC system.

Zhao et al. developed a novel counter-flow IEC module and conducted various sets of investigation into its performance using both theoretical and experimental methods [12,28,30–32]. In terms of computer simulation, the equations governing the heat and mass transfer between air, water and exchanging plate within the dry and wet channels of the IEC unit was coupled and solved using the finite-element differential approach. The Newton Iterative Method was applied to the simulation process. The model predicted that the wet-bulb effectiveness of the cooler could be as high as 130% under the UK's summer outdoor air design condition (28 °C db and 20 °C wb) if wet surface of the exchange plate is completely saturated. It also indicated that channel sizes, air velocities and secondary-to-primary air ratios had important impact to the cooling effectiveness and energy efficiency of the cooler, while the feed water temperature had less. Several geometrical and operational parameters were suggested to help design of the heat exchanger; these include: (1) channel spacing gap should be less than 6 mm; (2) length of the channels should be longer than 1 m or 200 time of channel spacing gap; (3) secondary-to-primary air ratio should be around 0.4; and (4) the intake air velocity should be set to 0.3–0.5 m/s.

Riangvilaikul and Kumar [97] presented a similar numerical study of a counter-flow dew point indirect evaporative cooler. The study developed a numerical model to simulate the heat and mass transfer process occurred in the dew point cooler. The governing equations were solved by employing finite differential approach and Newton iterative method to obtain temperature and humidity values of the air across the whole channel space. The modelling results were validated using the experimental data [24] under various inlet air conditions (typically covering dry, moderate and humid climates) and for different intake air velocities (1.5–6 m/s). Reasonable agreement was achieved between the numerical and experimental results, giving 5–10% of deviation in terms of the outlet air temperature and effectiveness, respectively. The study also showed that the predicted dew point effectiveness varied significantly from 65 to 86% when the inlet air humidity changed from 6.9 g/kg to 26.4 g/kg at the constant inlet temperature of 35 °C. In order to achieve a wet bulb effectiveness greater than 100%, the cooler should be properly configured and operated at favourite conditions; these include: (1) the intake air velocity should be set below 2.5 m/s; (2) the channel spacing gap should be less than 5 mm; (3) the channel length should be larger than 1 m; and (4) ratio of the working to intake air should be set between 35 and 60%.

Bruno [98] carried out an experimental study into the operational characteristics of a novel dew point IEC unit equipped with a counter-flow flat-plate heat exchanger [33]. As a pre-cooling device of a refrigeration air conditioner in the commercial application, the dew point IEC could achieve a wet-bulb effectiveness of 93–106% when the average outlet air temperature was 17.3 °C. The annual energy saving of the system relative to the equivalent refrigeration air conditioning was in the range 52–56%. For residential application, the wet-bulb effectiveness of dew point IEC was in the range 118–129%.

Based on the previous studies [31,99], a comparative study of cross-flow and counter-flow heat exchangers based on M-cycle [100] for dew point cooling was conducted [28]. Both configurations of heat exchangers were theoretically and experimentally investigated to identify the difference in cooling effectiveness under the parallel structural/operational conditions, optimise the geometrical sizes of the exchangers and suggest their favourite operational conditions. Through development of a computer model and experimental testing and validation, a parametric study of the cooling performance of the counter-flow and cross-flow heat exchangers was carried out. The comparison between the simulation and experimental results indicate an acceptable error range of 2–10%. The results showed the counter-flow exchanger offered greater (around 20% higher) cooling capacity, as well as greater (15–23% higher) dew-point and wet-bulb effectiveness when equal in physical size and under the same operational conditions. The cross-flow system, however, had a greater (10% higher) Energy Efficiency.

In summary, the M-cycle dew point cooling can achieve 80–120% of wet-bulb cooling effectiveness, 15–30% higher than conventional IEC system. The system could achieve enhanced COP as high as 8–20, thus leading to 10–20% reduction in fossil fuel energy consumption relative to the normal IEC system. For a typical cross-flow heat exchanger, its design limitations are (1) the intake air velocity should be set below 2.5 m/s; (2) the channel spacing gap should be less than 5 mm; (3) the channel length should be larger than 1 m; and (4) the secondary-to-primary air ratio should be set between 35% and 60%. The counter-flow exchanger offered greater (around 20% higher) cooling capacity, greater (15–23% higher) dew-point and wet-bulb effectiveness, and lower (around 90%) energy efficiency than the equivalent cross-flow heat exchanger. For computer modelling, the finite differential approach and Newton iterative method were commonly used and the experiment results indicated the established model can achieve the reasonable accuracy (less than 10%) in predicting the operational performance of the IEC.

4.6. Social-technical studies including energy saving, costing, payback, life cycle analyses, as well as environmental impact

Social-technical studies of the IEC systems were undertaken by a number of researchers. These involved evaluation of the

feasibility of the combined DEC/IEC systems or IEC systems alone for use in residential and commercial application under various climatic regions [3,10,12,23,33,45,55,89,95,101,102], and analyses of costing, energy saving, payback, life cycle as well as carbon based environment measures related to IEC system manufacturing and applications [10,16,25,27,29,84,101,103,104].

Energy saving potential associated with the IEC was studied by a number of researchers. Maheshwari et al. [10] presented an analytical investigation using the field testing results of an IEC unit with capacity of 1180 l/s air-flow rate and the recorded weather data in coastal and inland locations in Kuwait. The cooling outputs and power consumptions of the IEC and the packaged refrigerated air-conditioner of the same capacity were estimated; the results indicated that the IEC unit, when being used in the inland and coastal regions of Kuwait, could obtain 12,418 kW h and 6320 kW h of seasonal energy savings compared to the same sized conventional mechanical vapour compression refrigeration based air conditioner.

Heidarinejad et al. [23] investigated a two-stage IEC/DEC system used in various climate regions in Iran, with particular focus on the issues of thermal comfort, power saving and water consumption. The study indicated that more than 60% of power saving could be obtained by using this system in comparison with the conventional mechanical vapour compression systems with the same capacity; while the water consumption by the former was 55% higher. Based on this study, Delfani et al. [27] experimentally investigated the performance of the IEC to pre-cool air for a conventional mechanical vapour compression system (packaged air conditioner) for four cities in Iran. Two air simulators were designed and used to simulate indoor heating load and outdoor design conditions. By using the experimental data and an appropriate analytical method, the performance and energy reduction capability of the combined system during the cooling season operation was evaluated. The results indicated that the IEC unit could take up around 75% of total cooling load and save around 55% of electricity consumption compared to the sole use of the packaged unit air conditioner.

Feasibility for use of IEC in various climate regions was also considered. Jiang et al. [45] presented the feasibility of using a newly developed indirect evaporative chillier in different parts of the world by analysing the design climatic data derived from the ASHRAE handbook 2001. The paper indicated that the technology is suitable for use in dry climatic regions in the world e.g., West America, North France, Germany, Poland, Austria, Holland, most regions of Russia, Northwest China, Mongolia, Saudi Arabia, Kazakhstan, certain regions in India, and most regions of Australia. Duan's research [95] analysed the feasibility of using a new dew point cooling system (based on M-cycle) in China and European countries, taking into account of local weather conditions, availability of water source and water consumption. In this paper, the cooling capacity of such a system under various regions of China and European countries was estimated. The associated energy saving, economic measures (bill reduction) and environment impacts (carbon reduction) relative to conventional mechanical vapour compression system were also given quantitative analyses. It is concluded that the M-cycle based dew point system is suitable for most regions within EU countries and China, but unsuitable for some regions where the air is too humid to be dealt, e.g., Venice, Rome, Shanghai, Guangzhou etc. Lower humidity results in a higher difference between the dry bulb and dew point temperature of the air, which will benefit to the system in terms of enhanced cooling performance. Tap water has a suitable temperature to feed the system for cooling, with a water consumption rate in the range 2–2.5 l/kW h output. The cooling output of the system ranges from 1.6 to 5.2 W/m^3/h air flow rate, depending upon the region where the system is applied. For a 100 m^2 building space with 30 W/m^2 cooling load, the required air volume flow rate varies with application location and is in the range from 700 to 1700 m^3/h. This building space consumes 50–60 l of water daily. Compared to the mild or humid climates, the dry and hot climates need less air volume flow rate and less water. Compared to conventional mechanical vapour compression refrigeration based system, the dew point system has significant higher potential in saving energy bill although its capital cost is slightly higher. The estimated payback period of the dew point system is around 1.05–1.8 years, and the life cycle cost saving is in the range 2500–4700 Euros, depending upon the area the system is being used. By using the dew point system, the estimated annual carbon emission reduction potential is approximately 30,000 t across whole range of Europe area.

Farmahini-Farahani and Heidarinejad [54] carried out a theoretical study into the feasibility of using a combined system comprising a two-stage IEC/DEC, the radiative cooling panels and the first-stage pre-cooling coil in four cities in Iran, which have hot, dry, hot and dry, semi-humid climatic characteristics during the summer season. It was intended to generate the cooling water at night time by using the radiative panels; this amount of water was then stored and at the day time, delivered to the pre-cooling coil to cool down the intake air. This paper reported that the combined system could obtain 100–110% of wet-bulb effectiveness, which is around 9% higher than that in the two-stage IEC/DEC system.

Joudi and Mehdi [102] reported a case of utilizing an indirect/direct evaporative cooling system in a typical Iraq house. To cope with the changing cooling load, four different operational modes were implemented and put into alternative use. A dedicated analyses and comparison among these operations suggested that the system would obtain a higher level of energy efficiency when utilizing the relatively cold indoor return air, instead of the warm outdoor fresh air.

Economic aspects of the IEC systems were also discussed. Taking the same sized conventional air conditioner (AC) as the reference, Navon and Arkin [103] investigated the economic benefit and thermal comfort relating to utilization of a combined DEC/IEC system in a residential building in Israel. The life cycle cost was calculated by using the annual equivalent costs (AE) of the DEC/IEC and AC, as well as the estimated initial cost of the DE/IEC system. The results indicated that the economic benefit relating to use of the DEC/IEC is very promising owing to its significant electricity cost saving over the conventional AC.

Jaber and Ajib [25] designed an indirect evaporative air-conditioning for the typical Mediterranean residential buildings and studied the economic benefit relating to utilization of such a system. The results indicated that most of the cooling load of the buildings could be matched by using an IEC unit with the air flow rate of 1100 l/s. If such a IEC system were mounted in 500,000 Mediterranean residential buildings, as the replacement of conventional mechanical vapour compression refrigeration systems, the estimated annual energy saving and CO_2 emission reduction would be around 1084 GW h and 637,873 t per annum, respectively. The payback time of the implementation would be less than two years.

5. The current market profile and potential barriers existing for marketing exploitation

5.1. Current market profile

The information relating to IEC productions and engineering practices were briefed in Tables 1 and 2. In general, one-stage IECs are unable to provide sufficient cooling to buildings and thus, combination of IECs with other cooling devices, i.e., DEC, mechanical vapour compression type, heat pipe, heat recovery, chiller and

desiccant system, has become a trend of future technical and commercial development. Owing to the advantages of the IEC technology, extensive global commercial opportunities have been explored and market for IEC application is stilling expanding. According to the survey undertaken by Bom GJ et al. [105], nearly 20 million residential evaporative coolers were under operation across the world in 1999; of which 8–10 millions were placed in India, and around 4 millions in America, Australia, South Africa, Pakistan and Saudi Arabia.

Throughout USA (especially its southwest region), the ratio of the evaporative coolers in the whole air conditioning market was around 5% [42] in the commercial building sector. A number of organisations in California, including Pacific Gas and Electric, Sacramento Municipal Utility District, and Southern California Edison [105], delivered several debating programmes to discuss the EC related economic, environment and social benefits, with the aim of promoting use of the direct, indirect, hybrid and two stage evaporative cooling systems. In New Mexico, large quantities of evaporative cooling systems (mainly IEC/DEC) were installed in Schools [46]; this installation still grew at the rate of around 100 units each year.

In Australia, evaporative cooling products have occupied 20% of the air conditioning market since 2005. Use of the evaporative air coolers was mainly found in dry and hot climatic regions, particularly the southern Australia [106].

Potential application of IEC/DEC systems in European countries were also analysed [3,89]. Considering the expected increase in ambient temperature in the future decades, the European market for the IEC/DECs will be predicted to be steadily growing. In the UK, the estimated annual sale for the IEC/DECs would be around 40 millions, taking up roughly 5% of the full air conditioning market.

In China, around 40% of its territory (mainly Northwest region) was located at dry and hot climatic region which is ideally suitable for DEC/IEC application [107]. Over the recent years, the EC market has been rapidly growing owing to the users' increasing interest in applying energy efficient measures. As the indirect and hybrid evaporative cooling systems have less climatic restriction in application, its potential market is expected to be substantial. Between 1998 and 2009, quantities of the evaporative air coolers installed in China have increased from thousands to half a million [107]. Currently, there are over 160 IEC/DEC manufacturers in China who are producing various systems suitable for use in industrial, agricultural and commercial buildings [108,109].

To summarise, the combined operation of the IEC, DEC and mechanical vapour compression system could remove the climatic barrier in existence for use of IECs. It, meanwhile, could also significantly reduce the primary energy consumption caused by air conditioning operation, which is the case referred to conventional mechanical vapour compression systems [105]. This method therefore has potential to replace conventional mechanical vapour compression systems and presented significant market prospect. Based on the above market and technical reviews, the authors predicted that the market ratio of the EC (including IEC and DEC) in the whole air conditioning sector would achieve around 20% in the next 20 years.

5.2. Potential market barriers

Although significant market space has been exploited with the IEC technology, certain technical and non-technical barriers are still in existence and these have become the resistance to further market penetration. The identified technical barriers include: (1) relatively lower cooling effectiveness; (2) smaller temperature reduction potential; (3) larger geometrical sizes; and (4) higher dependency to the ambient condition. These barriers made the IEC systems unsuitable for independent operation in buildings [1,46,104,105,110] but the combined operation between the IEC and other cooling devices would be a solution. The non-technical barriers lie in [101]: (1) building matching; (2) use of land and architectural aesthetics; (3) local legislation on water use; (4) potential discomfort; (5) lack of standardisation; and (6) limited public awareness. The technical barriers will be resolved by the continuous advance in R&D; while the non-technical barriers will be mitigated through effective and organised dissemination activities including publications, conferences/seminars/workshops, governmental and community involvement, lecturing, medium broadcasting, as well as social movements etc.

6. Future research focuses and trend of development relating to the indirect evaporative cooling (IEC)

The current/past R&D works and commercial activities have created significant technical advance and market development in IEC technology. These, however, also help identification of the problems, difficulties and barriers that are still in existence, which in turn stimulate the development of the forthcoming research and industrial activities.

In line with the above review based study, future research and development activities related to the IEC may be (1) heat exchanger structure and material; (2) water flowing, distribution and treatment; (3) incorporation of the IEC components into the conventional air conditioning products; (4) economic, environment, and social impacts; (5) standardisation and legislation; (6) public awareness and other dissemination measures; and (7) manufacturing and commercialisation.

In terms of heat exchanger for the IEC, the current structure is mainly based on the flat-plate stacked form, which was found to be an easy-making, cost effective and energy efficient way of conducting indirect cooling of air. However, if the flat plate is reshaped into the wave form with the narrow straight stripes as the supporters between the adjacent plates, the heat exchanging area per unit of its width will increase by 30–40%, which subsequently increases the heat transfer rate of the heat exchanger unit by 15–30%; as a result, the cooling effectiveness of the system would increase by 10–20%. In terms of material, one-side water-proofed fibre paper was thought to be the favourite choice. However, its hardness, durability and water permeability were found to be unsatisfactory. Study of material should be focused on improving the hardness, durability and water permeability of the materials, which may be based on the currently available material with adequate chemical treatment to its surface, or finding the alternative material that can obtain enhanced performance in terms of the above measures.

In terms of water flowing, distribution and treatment, the current researches are far from satisfactory. Effect of the water flow speed across the wet surface of the exchanging plate on the cooling effectiveness of the heat exchanger was not yet investigated, and the flow patterns (current counter, opposite counter, current cross, and opposite cross) of water across the wet surface of the plate was also not given detailed consideration. Ways of water delivery and spray and their potential of creating even distribution of water across the surface of the plate are also the issues to be addressed. Further, method of treating water to keep its cleanness and prevent contamination of the wet surface of the plate is regarded as a difficult topic, which is worthy of further investigation.

in terms of the integration of the IEC with conventional air conditioning products, the currently available system modes are IEC/DEC, IEC/DEC/vapour compression refrigeration, IEC/desiccant cooling, and IEC/water chiller. However, more potential operational

modes are worthy of exploration and these may include (1) integration of the IEC into fan coil units; (2) integration of the IEC into air handle units; (3) integration of the IEC into a cooling tower to make chill water; (4) integration of the IEC into solar driven desiccant bed/wheel systems; (5) integration of the IEC into the condensation sector of a Rankin cycle power generating system. All these works expect to explore significant energy saving potential as the new trials for building air conditioning and power supply.

Economic, environment, and social impacts relating to the IEC are the issues that received less consideration in previous researches. Owing to the short history of the technology, the production scale of this type of products is still relatively immature compared to the conventional mechanical vapour compression refrigeration systems, and its practical application is limited to the several favourite climatic regions and (or) combined operation with other air conditioning devices including conventional mechanical vapour compression systems. On this circumstance, the economic, environmental and social impacts relating to the IEC were not given full range of investigation and no clear knowledge and understanding of these issues were yet established in most people's mind including the professionals. This will be another direction to be focused in relation to the IEC.

Standardisation, regulations and legislations are also the issues worthy of further investigation. Current studies into these aspects are not well established and also restricted to certain regions and countries in the world. This has caused certain difficulties in evaluating the product performance and assessing associated engineering quality. The future work on this subject will overcome this deficiency and expect to formulate complete and fully justified national/international standards/legislations that will promote development of the IEC technology.

The IEC, compared to the conventional mechanical vapour compression systems, is still relatively new technology and is less familiar to public including some of professionals. Organising specifically designed activities e.g., workshop, seminar, exhibition, onsite visit, demonstration as well as lectures, and publicising the research results in dedicated ways e.g., conference, journal, leaflet, brochure as well as media report, would help propaganda the knowledge relating to the technology and its associated benefits. This will promote its potential application in buildings and thus help win the fast acceptance and familiarity by the public.

Finally, the technology will need to be converted into massive producing and market attracting commercial products. The commercialisation work is currently under way but further speed-up measures should be brought into realisation.

7. Conclusions

This paper undertook a review based study into the Indirect Evaporative Cooling (IEC) technology in terms of its background, originality, current status, research and industrialisation achievement, market prospects and barriers, as well as future focuses on R&D and commercialisation. This work will be of great significance to promoting wider application of the IEC technology in buildings and thus contribute to realisation of low (zero) carbon air conditioning for buildings and associated energy saving and carbon emission measures.

The IEC originated at around 2500 B.C. and is now developed into a widely accepted technology in air conditioning sector. The IEC has advantages of conducting cooling of air using principle of water evaporation with no moisture being added into the air. This creates a comfortable space environment using the reserved energy in atmosphere rather than fossil fuel depended electricity, thus making it a potential alternative to the conventional mechanical vapour compression refrigeration systems. With the continuous technical advances in this specific area, especially the innovated M-cycle operation and associated heat and mass transfer and material studies, the cooling performance of an IEC system has achieved significant enhancement which allows as high as 80–90% of wet-bulb effectiveness to be obtained, while its cooling EER approaches 30–80. In a typical heat and mass exchanger for use in indirect evaporative cooling, the static pressure drop of the air in dry and wet channels is found to be in the range 60–185 Pa and 100–500 Pa, respectively, and the ratio of the working to product air is in the range 0.3 and 1. In terms of the structure of an IEC heat and mass exchanger, the flat-plate-stack is the commonly used form which enabled either cross- or counter- air flow patterns to be obtained; however, other forms of heat exchangers including tubing, heat pipe and wave structure, are also available choices. In terms of material for making heat/mass exchanging components (plate, tube etc), the single side water proofed cellulose fibre is the most common option; however, aluminium plate/tube with single side wicked (grooved, meshed, toughed etc), and ceramic plate/tube with single side water proofing were also acceptable alternatives. Treatment to materials to enable enhanced hardness, durability and water permeability is one of the future research focuses. Further, ways of water delivery and spray and their potential to create even distribution of water across the surface of the plate are also the issues to be addressed. Method of treating water to keep its cleanness and prevent contamination of the wet surface of the plate is another issue to be studied in the future.

Although significant progress has been achieved in developing the IEC technology, several inherent difficulties still remain with this subject, namely (1) relatively lower cooling effectiveness; (2) smaller temperature reduction potential; (3) larger geometrical sizes; and (4) higher dependency to the ambient condition. These drawbacks limited its wider application in air conditioning for buildings and as a result, the combined use of IEC and other cooling devices including conventional mechanical vapour compression refrigeration has become the common approach for the current, and potentially future, trend of the IEC technology development. Current operational modes for this combined system include (1) IEC/DEC system; (2) IEC/DEC/mechanical vapour compression system; (3) IEC/desiccant system; (4) IEC/chilled water system; as well as (5) IEC/heat pipe system. The future potential of the combined operation will be to develop the IEC incorporating fan coil units, air handle units, cooling towers for chilled water making, solar driven desiccant cycle, and Rankin cycle based power generation system.

Standardisations, regulations and legislations are the issues to be fully studied and the current status on standardisation of the IEC is far from mature. Further, the public awareness through proper dissemination activities will be one of the important concerns. All these events will eventually contribute to realisation of wide range of production, marketing and building installation of the IEC products. It is predicted that in the next 20 years, the IEC and IEC related systems will take up 20% of air conditioning market in buildings, with particular focus on dry and hot climatic regions including Middle East, East Asian, North American, African and Part of Europe.

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